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1. Introduction to the “Finding the limits of the *limes*” project

This research was undertaken as part of the “Finding the limits of the *limes*” project which was run between 2012 and 2017 (NWO Project number: 276-61-005; Verhagen 2011). The main ambition of the “Finding the limits of the *limes*” project was to develop quantified spatio-temporal scenarios of agrarian production of the Lower Rhine delta from the Early Roman period to the end of the Dutch *limes* (15BCE to 270CE). It sought to model economic and spatial relations between the Roman army and the local population. In addition to modelling the development of settlement patterns and transport networks (Groenhuizen 2018), modelling the interactions between arable farming, animal husbandry and fuel, and timber collection was a key ambition of the project.

There are great uncertainties related to how the socio-economic system of the Dutch Roman *limes* zone was organised and the impact that the presence of the Roman army had on this organisation; the logistics of provisioning the military and urban settlements that developed in the Roman period in the region; and the impact on land use. The research motivation for this project was to address these uncertainties as they have largely only been dealt with in general terms. The project utilised spatial dynamical modeling which is a useful tool when exploring development of landscapes over time. The use of spatial dynamic modelling in Roman archaeology was, at the time, not prevalent. The Dutch Roman *limes* zone was an apt testing ground for using this type of tool owing to the extensive archaeological and palaeo-environmental data set available from decades of archaeological research. The project sought to address major challenges when using computational modelling in archaeology. It is hoped the direct outcomes of this project (new and unique computational tools developed by the project) will have useful wider applications for Roman studies and archaeology. Two major archaeological research questions have been addressed by this project. The first question addressed is the potential for surplus-based agricultural production. This thesis focuses on addressing this question. The second question concerns the logistics and mechanisms for transport and distribution of goods in the region.

The research presented in this thesis specifically tackles several methodological and theoretical questions posed by the project. Firstly, it addresses how spatial dynamical modelling can be used to improve understanding of agricultural processes, not as separate tasks but interdependent processes by integrating them into a single model. Secondly, it has shown how extensive archaeological and palaeo-environmental data can be incorporated into a simulation and how ‘expert judgement’ models can be translated into formal models. Concerning theoretical questions, this research has considered whether scenarios developed by formal simulation models can be used to explain the archaeological and palaeo-environmental record. It has generated new hypotheses relating to the way agricultural production could have been organised. At the core of the research presented here is the production new results of the impacts that natural and socio-cultural factors had on the development of agriculture in the region

To answer these questions, this sub-project has developed a spatial-dynamic simulation model to simulate the interactions between different tasks of agriculture. The simulation model incorporates palaeo-environmental and archaeological data from the region and has converted several “expert” judgement models into formal sub-models. This has created a new tool for Dutch Roman archaeology making use of the intensive research that has already been undertaken for some 30 years in the region. The model was used to simulate several scenarios developed to experiment with different agricultural behaviours and strategies. The modelling results were analysed to produce new hypotheses regarding the possible ways that surplus production may have been organized in the Dutch *limes* zone during the Roman period. It has also sought to

include how natural and socio-cultural factors could have affected agrarian production. The results were also compared with the archaeological and palaeo-environmental record where possible to provide explanations for how they arose from the activities of farmers in the past.

1.1. Research outline

This research is presented in the following order. Firstly, an overview of the current state of knowledge is provided in chapter 2. This overview covers briefly the historical and archaeological knowledge related to the political development of the Lower Rhine delta from the Late Iron Age to the collapse of the Dutch *limes* in c. 270CE. In addition, a description of the natural environment based on palaeogeographic reconstructions is provided. Specifically concerning agriculture in the region in the past, the archaeobotanical and zooarchaeological sources are discussed for what they reveal about diet and the agricultural economy in the past. The evidence for surplus production in the region is also discussed with particular focus on recent modelling approaches to landscape capacity of the Lower Rhine delta.

In light of the current state of knowledge and the aims of the “Finding the limits of the *limes*” project provided above, the motivation for the approach undertaken in this research is given in chapter 3. The research aims and objectives of this research are explicitly provided too. In chapter 4, the agent-based model developed for this research, ROMFARMS, is described in detail after a justification of the methodological approach is given. In the following chapters, the results from using ROMFARMS to simulate multiple scenarios of agricultural production are analysed. Initially, in chapter 5, the subsistence-based economy typical of the Late Iron Age in the Lower Rhine delta is discussed. The discussion reveals new hypotheses about the baseline economy before the arrival of the Roman army which allows a comparative discussion of the impact of a shift from subsistence-based to surplus-based agriculture. In chapter 6, different strategies of surplus arable production are discussed with a focus on how the availability of land and labour limitations presented limitations and opportunities under different conditions for farmers in the past.

The results discussed in chapters 5 and 6 are based on simulations using hypothetical, randomly-generated landscapes. In chapter 7, subsistence- and surplus-based agricultural strategies are simulated once more but in reconstructed landscapes using palaeogeographic data available for the region. This chapter focuses on the interplay between cultural and natural conditions on agricultural productivity specifically in the Lower Rhine delta. Using new results related to agricultural production, chapter 7 also provides new results related to the supply and demand of grain from military settlements, towns and *vici* in the region, both from humans inhabiting these settlements as well as animals. The results are used to produce new hypotheses regarding the possible way in which surpluses were transferred from rural settlements to consumer-only settlements in the study region. In the final chapter, chapter 8, the research is synthesised. ROMFARMS is described and compared with the state of the art in agent-based modelling approaches to agriculture in the past. The results are collated and the implications that new hypotheses could have on the archaeology of the Dutch *limes* zone are discussed. Finally, ROMFARMS is evaluated for its limitations and opportunities for further development and future research foci using this unique and innovative tool for Dutch Roman archaeology are proposed.

2. Current state of knowledge

This chapter contains a brief overview of the archaeological context of the Lower Rhine delta in the Late Iron Age and Roman period. It begins with a brief overview of political developments in the region throughout the period of study (12 BCE to 270 CE), including settlement history and the palaeogeographic context. A discussion of the current state of knowledge regarding the diet of the inhabitants of rural, military settlements, and urban settlements as well as the agricultural economy of the region is provided. For the latter, there is a focus on the archaeobotanical and zooarchaeological evidence related to animal husbandry, arable farming, and fuel and timber collection. A description of the types of evidence is also given. Finally, a description and evaluation of previous attempts at modelling the agricultural economy of the Dutch Roman *limes* zone is provided, including new knowledge gained from these methods as well as scope for development.

2.1. The Lower Rhine delta from Late Iron Age to Middle Roman period: the political and geographical context

Space and the remit of this research do not permit more than a brief description of political developments of the Lower Rhine region in the Netherlands during the Roman period. Nevertheless, the major findings of this research must be placed within historical context. The region that would later become the Dutch *limes* zone in the Netherlands is mentioned first in the historical record by Caesar (*BG*, 4.10), but it is evident that he had no real interest in the region (Willems 1986, 358). Roman interference in the region remained restricted and the region took little part in inter-regional networks until the founding of the first military camp (*castra*) between 19 and 16 BCE at Nijmegen (Willems 1986, 198-199; Driessen 2007) (see figure 2.1 for locations of military settlements, towns and *vici* in the study region). This camp, perhaps housing up to two legions, was subsequently abandoned by 12 BCE (Driessen 2007). By the time of Drusus' campaigns in the region (12-9 BCE), native peoples in the Lower Rhine area can already be divided between the Cananefates of the western region and the larger group of Batavians in the eastern parts of the region (Willems 1986, 206; c.f. De Bruin 2017 who presents a later date of c. 50 CE for the formation of the Cananefates as a separate community).

Some twenty years after the abandonment of the first *castra* at Nijmegen, the founding of three further fortifications took place (Vechten in 4/5 CE; Velsen in 15/16 CE; and Meinerswijk in 10-20 CE). The majority of building works were undertaken in the 40s CE when the majority of forts were constructed on the southern bank of the Rhine, assumed to initially have been placed to protect shipping along the Rhine (Graafstal 2017; Polak *et al.* 2004a). In addition, a larger *castra* was constructed at Nijmegen as well as a series of watchtowers between the fortifications. Willems (1986, 25) attributed this phase of building to the "final abandonment of the old plans for expansion into Germany". In the Early Roman period (12 BCE – 70 CE), local groups and new groups were encouraged to settle in the Lower Rhine region which saw economic development and population increases. Unlike the area further south of the *limes* zone, the study region did not experience the development of specialised *villa* settlements. Instead economic continuity from the pre-Roman Late Iron Age is likely. The rural population remained in small settlements and engaged in mixed agriculture with a focus on pastoralism that was characteristic of the Germanic tribes of the region (see Roymans 1996). A treaty between the Batavians and Rome is inferred from Tacitus (*Germ.* 29) through which Batavians were exempt from taxation and instead supplied manpower for the army.

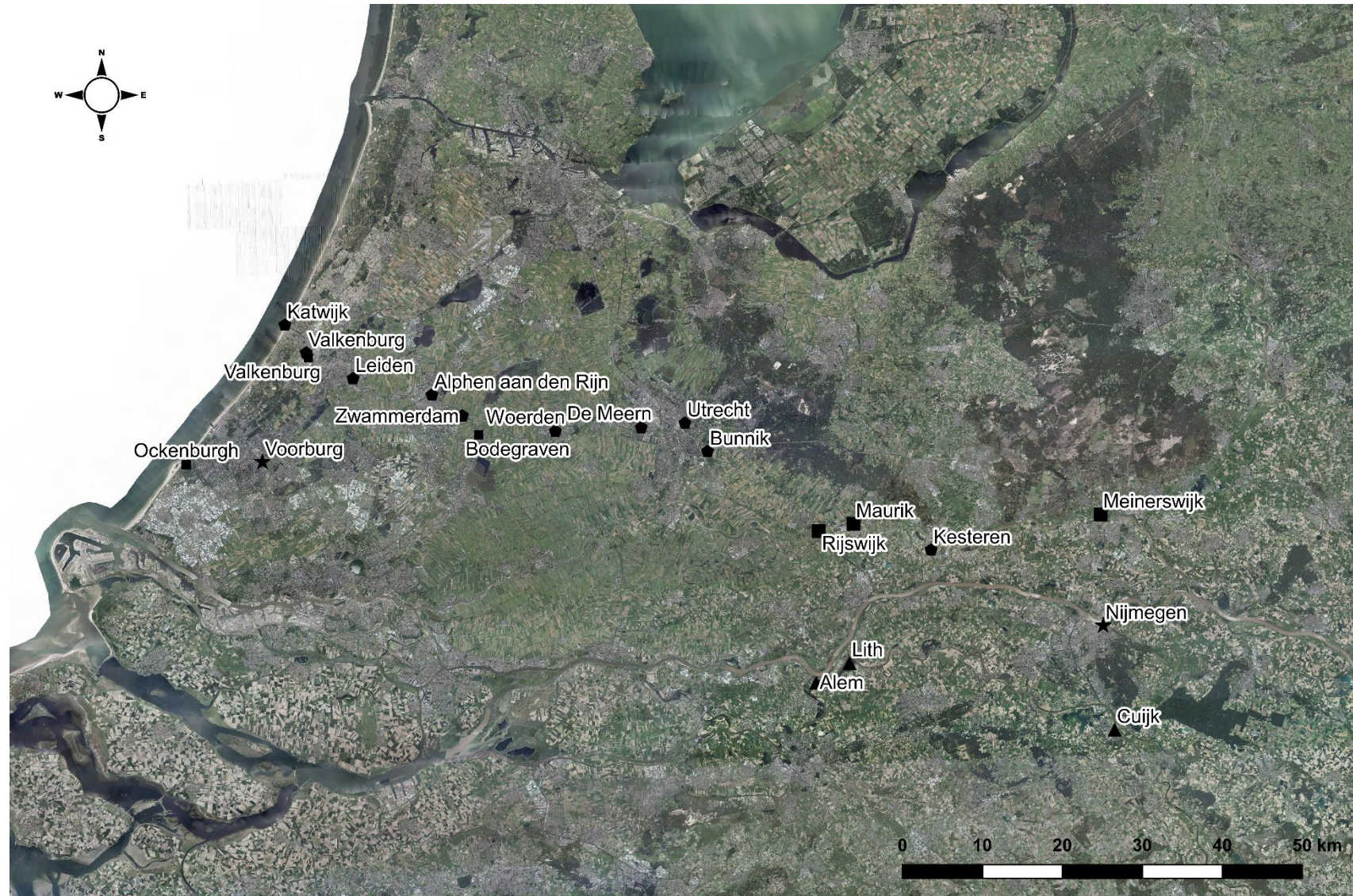


Figure 2.1. Location of known castella, civitas capitals and vici in the Dutch limes zone. ■ Castellum; ★ Civitas capital; ■ Mini-castellum; ◆ Castellum & Vicus; ▲ Vicus.

In 69/70 CE, a revolt among the tribes of the Dutch *limes* zone is attested from historical sources (Tacitus, *Hist.* 4). It is probable that from this point onwards, taxation was imposed on the local population (Groot 2008a, 25). After the destruction of many fortifications, the *limes* was rebuilt in the Flavian period and the region was formally incorporated into the empire as part of the province of Germania Inferior. At this point, the *limes* became the formalised North West frontier of the Roman Empire, and the fortifications were used to protect this frontier as well as shipping (Graafstal 2017; Kooistra 2009, 219 and Polak *et al.* 2004a). This process may have begun to occur earlier however (Willems 1986, 25). Economic development and population growth continued until c. 270 CE when the frontier collapsed during the Crisis of the 3rd Century.

2.2. Settlement history

Traditionally, the settlement densities of the Late Iron Age and Early Roman periods were thought to be low and in the earlier part of the Middle Roman period, a rise in the number and size of settlements has been repeated often (see e.g. Groot *et al.* 2009; Kooistra *et al.* 2013; Vos 2009; Willems 1986). An extreme decline in settlement density after the collapse of the *limes* in the third century is known from the archaeological record (Verhagen *et al.* 2016a). Site inventories for this study region suffer however from poor dating. A method developed by Verhagen *et al.* (2016a) using the principles of aoristic analysis showed that, after considering ambiguity and uncertainty of dating, these earlier studies were largely corroborated. Verhagen *et al.* (2016a) did suggest that there were previous underestimates of the number of Early Roman period settlements and overestimates of the number of Late Roman sites (see also van Lanen *et al.* 2018).

Estimating the number of farmsteads, houses or households per settlement is significantly harder given that many of the settlements are known only from surface finds (Vossen 2003, 424). Willems (1986, 236) assumed an average of three or four households per settlement, with five to eight people per household. Vossen (2003, 425) revised this estimated average number of households down to three and noted that large settlements of five or six households were exceptional. It was noted that settlements in the eastern part of the Dutch *limes* zone possessed a range of sizes from single farmsteads to larger settlements (*ibid.*, 424-425). An average for the western part of the *limes* zone studied by van Dinter *et al.* (2014) was assumed to be one to two households per settlement, an estimate repeated by Verhagen *et al.* (2016a, 313).

2.3. Workforce and population size

It is probable that for farmers in the Dutch *limes zone*, labour was required inconsistently throughout the agricultural calendar. Rosenstein (2004) suggested that the farmer on a small-scale may have worked harder at times than labourers enslaved to large *villa* estates. Within the rural community of the Lower Rhine delta in the Netherlands, the availability of manpower would have been a significant limiting factor to the community's production capacity. Among the Batavians and probably also other groups living in the Dutch *limes* zone during the Roman period, military recruitment of the male population was significant (see van Driel-Murray 2003, Vossen 2003 and Roymans 2004 for discussions on the military recruitment of local population groups in the region). In fact, "no other population group within the empire was as intensively exploited for recruitment purposes" claim Derks & Roymans (2006, 122). The actual number of recruited individuals has been discussed in several studies (see e.g. Alföldy 1968, Bloemers 1978, Willems 1986 and Vossen 2003). Verhagen *et al.* (2016b) demonstrated the negative impact on population growth that removal of young adult males from the marriage pool could have had. Recruitments also had a negative impact on the availability of labour. The impact of incomplete households on agricultural productivity in the study region was discussed briefly by van Dinter *et al.* (2014, 27-28) but there remains scope for further discussion.

2.4. Palaeogeographic context

Van Dinter (2013) and more recently Groenhuijzen (2018) have used a variety of sources to produce detailed palaeogeographic reconstructions of the natural landscape of the Dutch *limes* zone. Kooistra *et al.* (2013) and van Dinter *et al.* (2014) used the reconstructions of van Dinter (2013) to focus on the western area of the *limes* region (from Katwijk to Vechten). The eastern-most part of their study region was part of the Dutch River area. This was a landscape of active rivers flanked by levees and older stream ridges, and large areas of flood basins. The levees were the highest parts of the landscape and flooded rarely; the flood-basins were much lower parts of the landscape and flooded regularly. Large-scale deforestation of the landscape had already occurred over much of the Dutch *limes* zone prior to Roman occupation although some relict woodland did remain. The central part of the study area was characterised by narrow levees with large areas of eutrophic fen woodland either side. The fen woodland gave way to area of mesotrophic reed and sedge fields, finally ending with an area of nutrient-poor sphagnum peat. The western and coastal region contained the Rhine estuary where the highest parts of the landscapes, the levees, possessed nutrient-poor aeolian sands and were regularly intersected by dune ridges and barrier plains. The extended reconstructions conducted by Groenhuijzen (2018) provide descriptions of the most easterly part of the Dutch *limes* zone, where wider areas of levees were flanked by Pleistocene sands, fluvial terraces and cover sands. Each part of the *limes* zone possessed 'its own possibilities and limitations for living grounds, food production and the occurrence of wood' (Kooistra *et al.* 2013, 7).

Kooistra *et al.* (2013, 10) suggested that in their study regions, land use possibilities were largely the same in all areas. Groot & Kooistra (2009) similarly attributed different parts of the landscape surrounding the settlements at Tiel-Passewaaij to different elements of the agricultural economy. As such it can be assumed that the levees and stream ridges, as higher parts of the landscape and less prone to flooding, would have been used throughout the Dutch *limes* zone for arable farming and habitation. The flood basins were suitable areas of pasturing livestock and fodder production. Relict woodland that remained in stream ridges and levees containing willow, ash, elm, field maple and oak and flood basins containing alder would have been used for timber and fuel collection. Other landscape elements peculiar to specific regions would also have been used for specific activities: the dunes ridges in the western coastal region could have been used in the same way as levees, and the salt marshes located here were also excellent grazing grounds. Fen woodland would have been extensively exploited for collecting firewood.

2.5. Archaeobotanical and zooarchaeological evidence

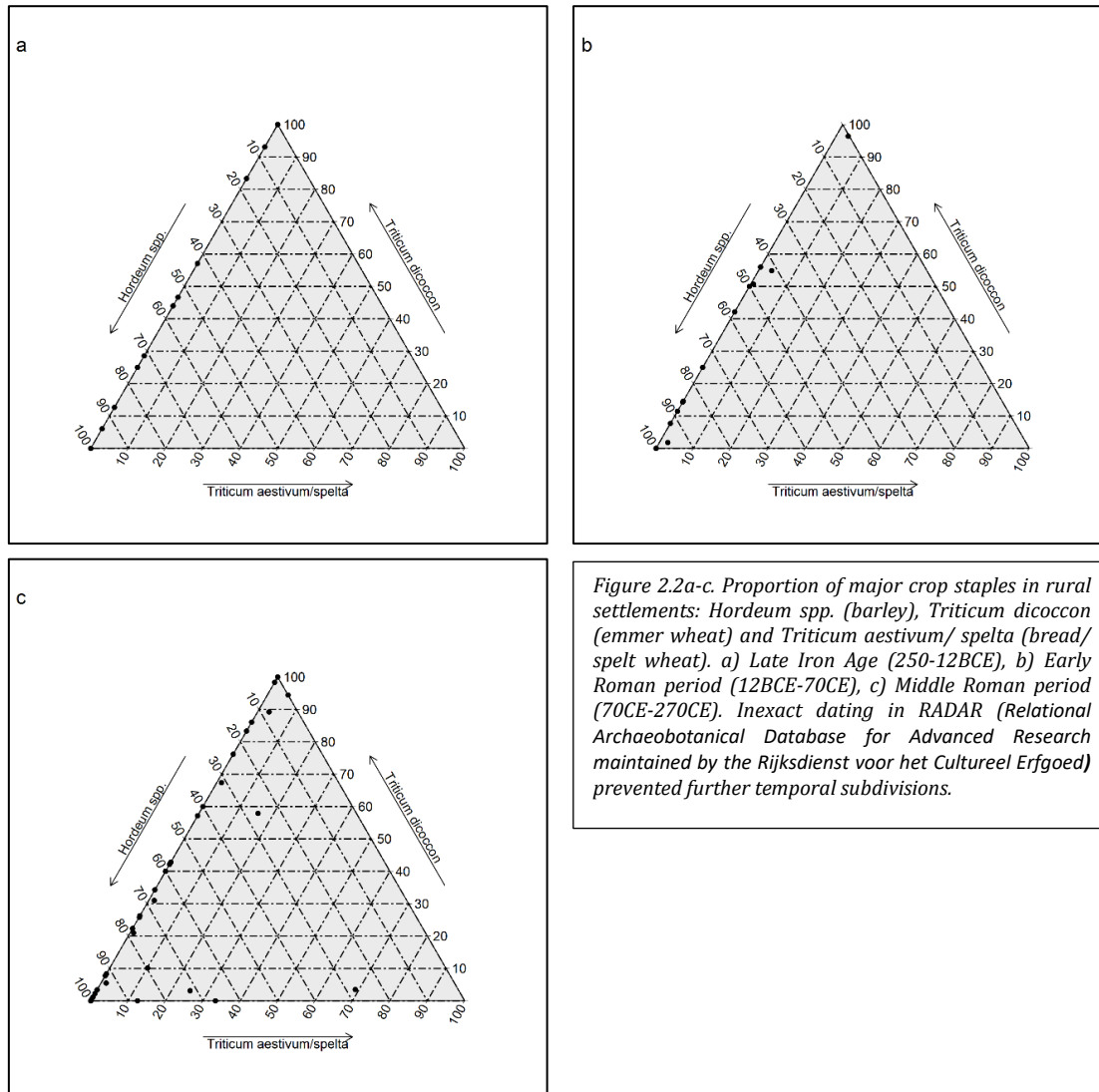
The majority of evidence for farming practices in the *limes* region both prior to the arrival of Roman soldiers and during occupation is taken from the substantial archaeobotanical and zooarchaeological record. For the former, assemblages are from both charred and waterlogged contexts. Anaerobic conditions owing to waterlogging produce species-rich assemblages with plants preserved that would not usually be preserved under normal conditions. Archaeobotanical assemblages from contexts in the Dutch *limes* zone contain, as well as cereal grains and chaff, oil-rich plants (e.g. *Linum usitatissimum* or *Camelina sativa*), condiments (e.g. *Anethum graveolens* or *Apium graveolens*) and fruits (e.g. *Sambucus ebulus* or *Prunus spinosa*). Many of these plants would unlikely come into contact with fire and therefore will not be preserved by charring but can be preserved by waterlogging. Waterlogging, however, presents its own difficulties particularly with distinguishing between naturally and culturally accumulated flora (Pearsall 2015, 86). The preservation of naturally accumulated plant remains is possible in waterlogged contexts. Whilst preservation by charring indicates that those plant remains preserved were likely to have been

brought to a site and formed part of the economy or diet of a site, waterlogged assemblages can contain both plants used by the inhabitants of a site and those occurring naturally in and around a site. Archaeobotanical assemblages do not usually contain all plants that were part of a site's economy or diet and can often contain plants that were not used or consumed by inhabitants.

Interpretations of past agricultural practices via archaeobotanical remains, in particular arable weed flora, are not straightforward given that the plants associated with arable fields found in sites are only part of the flora that grew in fields; the rest remain in situ in the fields themselves. The techniques used (ecological indices or phytosociological groupings) are also problematic as discussed by Charles *et al.* (1997). Interpretation of the exploitation of plant resources in the Dutch *limes* zone is hampered too by the absence of anthracological studies: there is significant knowledge regarding the exploitation of wood and timber for construction, however there is little knowledge regarding the exploitation of wood for fuel.

The Dutch *limes* zone also offers rich zooarchaeological assemblages that have been used extensively to reconstruct diet and the pastoral economy of the region. The principle that kill-off patterns have no direct link to actual herd compositions from faunal remains limits zooarchaeological interpretation unless the assemblage is from a catastrophic event in which an entire herd died. The inputs to the herd system can be inferred (e.g. birth rates and natural mortality) and the outputs are visible via the faunal assemblage, however the mechanism (e.g. slaughter rates) is usually invisible (Cribb 1987, 378). In addition, quantification of animal remains from zooarchaeological assemblages do not allow for translation to a total number of animals in site. It is also problematic in understanding if changes in increases or decreases of species and changes are relative. The problems related to the interpretation of management practices from mortality profiles are discussed in Groot (2008a, 37-38). Particular problems include the assumption of economic efficiency (farmers could exploit animals for multiple products), and social or ritual decisions may have played a part in the creation of a kill-off pattern too (*ibid.*, 37). Furthermore, animals may be missing from the assemblage such as those slaughtered outside the settlement or site, or those traded as a surplus commodity for consumers elsewhere (*ibid.*, 38).

Archaeobotanical and zooarchaeological evidence has helped to develop theories regarding agricultural strategies in the Dutch Roman *limes* zone. However, the issues highlighted above with these types of evidence, mean that some agricultural practices are hidden from the archaeological record. This means that whilst this study incorporates the most likely strategies employed by native farmers in the Dutch Roman *limes* zone, the list of practices analysed is not exhaustive.



2.6. Diet and economy: animals and plants

2.6.1. Staples and non-staples

Cereals constituted the larger part of the diet for the inhabitants of the Lower Rhine delta in the Roman period and represent what can be defined as staples with some degree of certainty (see table 2.1 for list of plants with an economic or dietary role in the Dutch *limes* zone from Late Iron Age and Roman assemblages). Cereals including bread wheat (*Triticum aestivum* L.), emmer wheat (*Triticum dicoccon* Schrank), spelt wheat (*Triticum spelta* L.), common millet (*Panicum miliaceum* L.), barley (*Hordeum* spp.), rye (*Secale cereal* L.) and cultivated oat (*Avena sativa* L. 1753) have all been found in varying quantities within the archaeobotanical remains found at rural, military and urban sites. In rural settlements emmer wheat and barley are most prevalent with very little spelt or bread wheat recovered. In military and civilian settlements, remains emmer wheat and barley are still encountered, however spelt wheat was found in greater quantities as well as some bread wheat. The relative proportion of the main staple grains (emmer wheat, barley and spelt wheat) are provided in figures 2.2 and 2.3. It is clear that emmer wheat and barley are characteristic “local” cereals, whereas spelt wheat is associated with military and urban settlements in the region.

As table 2.1 shows, whilst cereals formed the bulk of the plant-derived part of the diet, a wide range of different plants, fruits and nuts were present in assemblages from all types of settlements. Inferring specific use of non-staple plants is more complicated. Ascertaining use and cultivation of “garden” vegetables, for example, is problematic (Moffet 1988). Vegetative plants such as leaves and stems rarely survive or are often not recognised from archaeobotanical assemblages. In addition, these plants often have wild counterparts whose seeds and pollen are indistinguishable from cultivars. Matching the ancient name of plants whose use is known from ancient sources often carries substantial debate. For example, identifying and matching the Latin word *apium* to wild celery, cultivated celery or parsley was ‘the subject of lively debate’ (Andrews 1949, 91).

Plants did not only form part of the diet of inhabitants in the Dutch Roman *limes* zone but also had other economic roles. These include, among others, the use of their fibres, as dyes, as narcotics, and use in medicines. For the latter, although several medical works and pharmacopoeias exist from the Roman world such as works by Pliny (*Naturalis Historia*), Dioscorides (*De Materia Medica*), Hippocrates (*Corpus Hippocraticum*) and Celsus (*De Medicina*), it is difficult to identify plants used for medicinal purposes from archaeobotanical remains. As discussed above, it is often difficult to identify a modern plant from the ancient name given in the primary sources. It is also complicated, even if the plant is known as a medicinal plant, to certify its use as a medicinal plant given that many plants in the ancient world had numerous uses and a plant’s original function can be invisible. Only in exceptional circumstances can a medicinal use for plants be more obvious, such as when plants are found within structures used for healing and medicine. For example, plants found at the *valetudinarium* at Neuss were identified as for medicinal use because of their association with a place of healing (Davies 1970). As many plants that were used for medicinal purposes also grew wild, distinguishing between weed and medicine is often difficult. Evidence for use of narcotics or entheogens is even more limited and those listed in table 2.1 are provided only as they have known psychoactive properties. Opium may have been used in the Roman world as a narcotic (Scarborough 1997), as could have cannabis (Brunner 1973; van Amen & Brinkkemper 2009).

CATEGORY	NAME	COMMON NAME	NEDERLANDSE NAAM
CEREALS	<i>Avena sativa</i> L. 1753	Common oat	Haver
	<i>Hordeum vulgare</i> L.	Barley	Gerst
	<i>Panicum miliaceum</i> L.	Common millet	Gierst
	<i>Secale cereal</i> L.	Rye	Rogge
	<i>Triticum aestivum</i> L.	Bread wheat	Broodtarwe
	<i>Triticum dicoccon</i> Schrank	Emmer wheat	Emmertarwe
	<i>Triticum spelta</i> L.	Spelt wheat	Spelt tarwe
HERBS & SPICES	<i>Anethum graveolens</i> L ^a	Dill	Dille
	<i>Anthriscus cerefolium</i> (L.) Hoffm.	Chervil	Echte kervel
	<i>Apium graveolens</i> L.	Celery	Selderij
	<i>Brassica nigra</i> (L.) Koch.	Black mustard	Zwarte mosterd
	<i>Brassica rapa</i> L.	Turnip	Knolraap
	<i>Beta vulgaris</i> L.	Beet	Biet
	<i>Daucus carota</i> L.	Wild carrot	Wilde peen
	<i>Foeniculum vulgare</i> Mill.	Fennel	Venkel
	<i>Pastinaca sativa</i> L.	Parsnip	Pastinaak
LEGUMES	<i>Lens culinaris</i> Medikus	Lentil	Linze
	<i>Pisum sativum</i> L.	Pea	Erwt
OIL SEEDS	<i>Vicia faba</i> L.	Field bean	Tuinboon
	<i>Camelina sativa</i> (L.) Crantz (1762)	Gold-of-pleasure	Huttentut
	<i>Linum usitatissimum</i> L.	Flax	Vlas
	<i>Olea europea</i> L ^b	Olive	Olijf
	<i>Papaver somniferum</i> L.	Opium poppy	Maanzaad
NUTS & FRUITS	<i>Coriandrum sativum</i> L.	Coriander	Koriander

MEDICINAL & NARCOTICS	<i>Corylus avellana</i> L.	Hazel	Hazelaar
	<i>Ficus carica</i> L.	Common fig	Vijg
	<i>Fragaria</i> spp.	Strawberry	Aardbei
	<i>Juglans regia</i> L.	Walnut	Walnoot
	<i>Prunus persica</i> (L.) Stokes	Peach	Perzik
	<i>Prunus</i> spp.	Plum	Pruim
	<i>Prunus spinosa</i> L.	Sloe	Sleedorn
	<i>Rubus fruticosus</i> L.	Blackberry	Gewone braam
	<i>Rubus idaeus</i> L.	Raspberry	Fraamboos
	<i>Sambucus nigra</i> L.	Elderberry	Gewone viler
	<i>Vitis vinifera</i> L.	Grape	Druif
	<i>Hyoscyamus niger</i> L.	Henbane	Bilzekruid
	<i>Hypericum perforatum</i> L.	St. John's wort	Sint-janskruid
	<i>Plantago lanceolata</i> L.	Ribwort plantain	Smalle weegbree
	<i>Potentilla erecta</i> (L.) Räuschel	Tormentil	-
OTHER	<i>Solanum</i> spp.	Nightshade	Nachtschade
	<i>Verbena officinalis</i> L.	Vervain	IJzerhard
	<i>Reseda luteola</i> L. ^c	Weld	Wouw
	<i>Cannabis sativa</i> L. ^d	Hemp	Hennep

Table 2.1. List of common plant species from archaeobotanical assemblages from rural, military and urban settlements in the Lower Rhine region in the Roman period (12 BCE – 270 CE). ^a Also described as a potential medicinal plant. ^b Also used for the flesh of the fruit. ^c Weld was used to produce a red dye. ^d Likely, primarily, used for its fibre. It's use as a narcotic, whilst less likely, can not be fully ruled out.

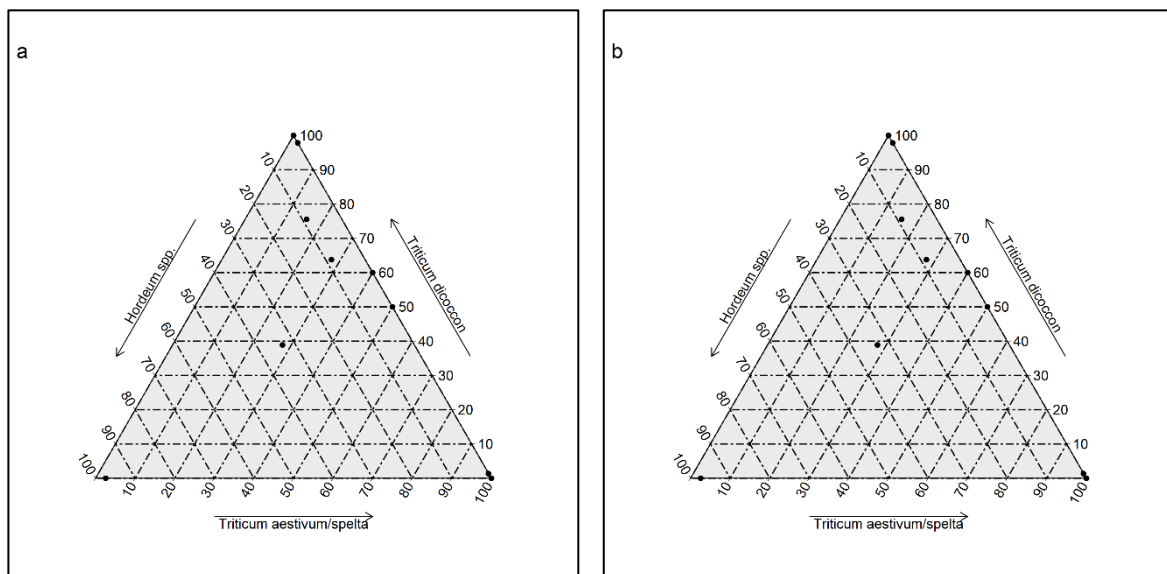


Figure 2.3a-b. Proportions of major crop staples in military/civilian settlements: *Hordeum* spp. (barley), *Triticum dicoccon* (emmer wheat) and *Triticum aestivum/spelta* (bread/ spelt wheat). a) Early Roman period (12BCE-70CE), b) Middle Roman period (70CE-270CE).

Some plants may have been considered luxuries in the study region during the Roman period, although their status as such was fluid (van der Veen 2003). Bakels & Jacomet (2003) concluded that in North West Europe luxuries had initially a significantly military characteristic, while later on the presence of luxuries diffused into urban and rural settlements. Where possible local cultivation occurred, removing the exclusivity of these products. Their continued use after Roman occupation is testament to their becoming regular parts of the “menu” (ibid.). For some plants, importation was the only way of access. Of particular note is fig (*Ficus carica* L.), a plant that rarely produces ripe fruit in the Netherlands (ibid.). These fruits would have to be imported from further south, although the distance of import did not mean they became luxuries. The ubiquity of fig in North West European Roman sites is indicative that fig did not become a luxury

(ibid.), although its inclusion within sacrificial deposits at the Fortuna temple in Nijmegen suggests a socio-religious importance (Vermeeren & Hänninen 1997). In this sense, whilst many luxuries were imported, not all imports were luxuries.

2.6.2. Arable farming in the Dutch *limes* region

Archaeobotanical assemblages from rural settlements in the Dutch *limes* region have been used to identify arable farming strategies from the Late Iron Age to the Middle Roman period. In the Late Iron Age, rural farmers cultivated six-row barley and emmer wheat. In some areas, common millet and spelt wheat were cultivated such as in the cover-sand areas north and south of the Rhine in the eastern part of the region. Rye and oat have been found in Late Iron Age contexts, but both are assumed to have been arable weeds rather than intentionally cultivated plants (Kooistra 2009, 223; see also van Zeist 1981, 183). Oil-rich plants such as flax and gold-of-pleasure may also have been cultivated by rural settlements (for the former see Brinkkemper 1991; Brinkkemper & de Ridder 2000; Hänninen 2005; van Beurden *et al.* 2007; Kooistra 2007; for the latter see Brinkkemper 1991, 1994; Hänninen 2005). There are few instances of pulses being cultivated including field bean (van Beurden *et al.* (2007). Fruits and nuts would have been collected from the local environment (Brinkkemper 1991; Brinkkemper & de Ridder 2001; Hänninen 2005). Despite the large range of plants that formed part of the economy and diet, it is likely that cereals had the biggest economic function. Palynological evidence points to already large-scale deforestation in the Late Iron Age and 'organised cultivated landscapes' (Kooistra 2009a, 223; see also Teunissen *et al.* 1987; Bunnik 1999; van Beurden 2002; Bakker 2003; Kalis & Meurers-Balke 2007; Kooistra 2008a).

Little change can be observed in the spectrum of plants cultivated and used among rural settlements in the first part of the Early Roman period (Kooistra & van Haaster 2001). At the rural settlement of De Meern LR546, however, remains of spelt wheat have been recovered (Kooistra 2008b). Coriander has been found here too (ibid.). It is unlikely that either would have been cultivated by local farmers, but they may have originated from the nearby fort at Vechten (ibid., 4-5). Nevertheless, even by the Middle Roman period, local farmers had mostly not adapted to the presumed tastes of the Roman army. The main crops cultivated locally remained six-row barley and emmer wheat. Millet, oat and possibly rye, were cultivated by some settlements but on a limited scale (see e.g. Lange 1990; Kooistra *et al.* 1998; Kooistra & van Haaster 2001; van Haaster & van Rijn 2005). There was little use or cultivation of exotics. The development of larger granaries was a significant change in this period which points to possible development in surplus production (Kooistra 2009, 227). There is a possibility that these granaries were not solely used for the storing of surplus grain for human consumption, however. Groot *et al.* (2009) calculated that the storage space of granaries at Wijk bij Duurstede- De Horden and Tiel-Passewaaij exceeding the carrying capacity of the local environment and concluded that the granaries were used also for the storage of animal fodder.

2.6.3. Provenance of plants

Assessing the provenance of crop plants in military and urban settlements was an important part of identifying the possibility of local supply. Inferring whether cereal plants originated from local rural settlements is not straightforward and relies on circumstantial evidence: similarities in the spectra of plants found, arable weed assemblages having characteristic "local" flora. In contrast, identifying those plants that originate from elsewhere is simpler. The presence of alien weed flora indicates cultivation elsewhere as does the ecological characteristics of some plants which preclude local cultivation. A detailed overview of the provenance of plants in both military/urban and rural settlements is provided by Kooistra (2009, 2012) which is summarised below.

Archaeobotanical assemblages from five samples at the earliest military installation in the region, Nijmegen between 19/16 BCE to 12 BCE, suggest a local origin with cultivated oat, six-row barley, common millet, flax and gold-of-pleasure which match the spectra of plants grown by Late Iron Age settlements in the region (De Hingh & Kooistra 1995). Importing of foodstuffs took place also as indicated by the presence of an olive stone (ibid.). Assemblages from those forts established twenty years after the abandonment of the first camp at Nijmegen, also point to a possible local procurement of some plants: flax, gold-of-pleasure, sloe and hazel have been recovered at Velsen (Pals 1997). Exotic finds were found here too which would have been imported (ibid.). At Meinerswijk, Teunissen *et al.* (1987) suggested the presence of *Cerealia*-type pollen was indicative of cereal production in the vicinity of the fort. Kooistra (2009, 226) suggested- in light of experimental evidence- that it was more likely the result of crop processing in the settlement (Diot 1992).

Assemblages from forts established in the latter part of the Early Roman period (Valkenburg, Alphen aan den Rijn, Woerden and De Meern) contain the same cereal plants and arable weeds as assemblages from nearby rural settlements (cf. figures 2.2 & 2.3). Remains from de Meern come not from the *castellum* but from a nearby watchtower associated with the military settlement (van Haaster 2007). Six-row barley and emmer wheat were present in all military settlements from this period. Both grain sorts could have come from local sources. The assemblage from the watchtower at De Meern contained no exotic weeds and the weed flora present was similar to the native spectra. Oat was also present in a majority of sites and in two sites, rye and common millet were also present. The presence of common millet points to the involvement of settlements north and south of the Rhine in local supply as common millet is a grain sort associated with the cover-sand areas north of the Rhine. Spelt wheat has been found in all military sites of the Early Roman period as well as non-native weeds such as corn-cockle (*Agrostemma githago* L.). Bread wheat has been found in three of the military sites named above. Evidence from a centurion's latrine pit at Alphen aan den Rijn revealed numerous other plant imports were consumed by the Roman army (Kuijper & Turner 1992).

A significant change occurred in the cereal spectra recovered from military and urban sites in the Flavian period. At Valkenburg, Roomburg, Woerden and De Meern, only spelt wheat, bread wheat, six-row barley and emmer wheat have been found. The former two were probably imported whereas the latter two could have been procured from local settlements. The presence of native weed flora further indicates, at least partial, local supply. Imports of plant-based foodstuffs undoubtedly continued. The shipwreck at Woerden in the late 2nd century and its cargo of weed- and insect-infested emmer wheat indicates that cereals that could be procured locally still needed to be imported from further afield (Pals & Hakbijl 1992).

2.6.4. Main livestock

Cattle was the most frequently consumed animal in the Dutch *limes* zone during the Roman period in military, urban and rural settlements. Among those sites analysed Lauwerier (1988), the proportion of cattle bones varies between 60 and 91.5% of the total number of fragments of consumed animals. Other domesticated animals consumed in the region include pig and sheep/goat. There is very little evidence of horse consumption in the Dutch *limes* zone (Lauwerier 1988), however, horses were an important part of the local agrarian economy. In the Late Iron Age there was a strong focus on cattle husbandry as part of the pastoral economy. Cattle dominates the species spectrum in rural sites in the Netherlands in this period (Roymans 1999; van Dijk & Groot 2013). Slaughter patterns indicate that cattle in many settlements were allowed to mature to adulthood. Whilst this can be indicated of exploitation for secondary products (e.g. milk or manure), Roymans (1996) argues that cattle in this period were important demonstrators of wealth and could have also been used in gift exchange. Meat would have remained an important

product (Filean 2006). Sheep/goat were largely exploited for meat in this period and perhaps milk (Groot 2008a; van Dijk & Groot 2013). Pig in the Late Iron Age was of limited importance (Groot & Deschler-Erb 2015, 454; van Dijk & Groot 2013, 180-181).

In the Early Roman period, changes in animal husbandry can be observed within zooarchaeological assemblages in the Dutch *limes* zone. Both changes in the relative proportions of domesticated species can be observed as well as changes in the way that these animals were exploited. Although trends can be observed, sites in the Dutch *limes* zone exhibit substantial diversity in animal husbandry practices throughout the *limes* zone (Groot 2016). From the Early Roman period onwards, cattle appear to lose their role within gift exchange (Roymans 1999, 296; van Dijk & Groot 2013, 184). This is possibly evidenced, according to Roymans (1996), by the increase in withers height of cattle observed from the Late Iron Age to the Roman periods. The maintenance of larger cattle points to the importance of the output of products they supply rather than the herd size. In particular, the surplus production of cattle for supply to military and urban settlements may be inferred from this change in status. In the eastern part of the *limes* zone for example, there is an emphasis of meat production from cattle and perhaps sheep/goat. However, some sites show that this changes by the Middle Roman period whereby cattle are slaughtered at much older ages than optimum meat production would indicate. It is possible that in this region cattle became important for the products supplied whilst living (manure and traction) indicating their role within a more intensive arable strategy (Groot 2008a; van Dijk & Groot 2013; Groot & Deschler-Erb 2015). The role that cattle may have played within the arable economy is further evidenced by some evidence of palaeopathological evidence on cattle bones associated with their use as draught animals (Groot 2005). Concerning manure as a valuable product supplied by cattle, it is clear Roman agronomists were well aware of the positive impact incorporating manure into arable land had (White 1970). Breeding cattle for manure (as well as traction) is regularly interpreted from zooarchaeological assemblages from rural sites in the Dutch Roman *limes* zone (Groot 2008a, 2008b; Groot & Kooistra 2009; van Dijk & Groot 2013). It is very likely that manure and traction were important products supplied by cattle husbandry. Cattle bones found in military and urban settlements also indicate cattle consumed there had reached adulthood suggesting local supply of sub-optimum cattle for meat consumption (Groot 2008a, 2008b).

In the Middle Roman period, the importance of sheep and goat continue to decline after an initial increase in some parts of the *limes* region in the Early Roman period (van Dijk & Groot 2013). By the Middle Roman period, the exploitation of sheep/goat has changed in some areas from exploitation of milk and meat to the exploitation of animals for wool, possibly as a surplus product (Groot 2008a; van Dijk & Groot 2013). In the Roman period in the *limes* zone, pig continues to be of minimal importance in rural sites, however it becomes somewhat characteristic of military site assemblages. A decline in pig consumption can be observed at military and urban sites in the region after the initial occupation however, pointing to the possibility that pig may have been brought by the army in the early years of occupation (Cavallo *et al.* 2008; Groot & Deschler-Erb 2016). The relative unimportance of pork production in the *limes* zone can be largely attributed to the lack of suitable landscapes, particularly oak and beech woodland (Groot 2008a, 69; Groot & Deschler-Erb 2015, 2016).

The possibility that local communities engaged in horse-breeding as a form of surplus production has been a recurring theme in archaeological studies of the *limes* region. The increase in number of horse bones found within bone assemblages, including the bones of foals, and the increased wither heights, point to the increasing importance of horse within the local community (Johnstone 2008; Lauwerier 1988; Nicolay 2008, 218-219). Nicolay (*ibid.*) denies specialised production in favour of intensive production despite the ubiquity of horse gear and the high proportion of horse bones in rural sites (Groot 2008b; Vossen & Groot 2009). Vossen & Groot

(2009) argue that the estimate yearly demand of 373-413 horses could have been supplied by the local settlements in the Lower Rhine delta.

2.6.5. Other animals

In addition to livestock other animal species have been recovered from faunal assemblages found in both military/urban settlements as well as rural settlements. Domesticated fowl have been found in small numbers in several native and non-native sites (Lauwerier 1988; Groot 2008a). Consumption of chicken also represents a military characteristic (Lauwerier 1988). Cavallo *et al.* (2008) have suggested that chicken too could have been used by the army in the earliest phases of occupation to fulfil their immediate needs before supply networks had been established.

Wild animals, fowl and fresh water fish have also been found (see Lauwerier 1986, 1988; Kuijper & Turner 1992; Groot 2008a; Groot & Kooistra 2009). In rural settlements, wild fauna could have served to supplement the diet, been useful for products such as fur, and the hunting of wild mammals may have had an important symbolic role (Groot 2008a, 66-67). For the military, wild animals would have been useful supplements to the soldiers' rations (Davies 1971).

2.7. Fuel and timber collection

Wood was an important resource for both rural, military and urban settlements. Wood was used for both building materials and fuel. However, the short description of the current state of knowledge given below shows that the region is lacking some crucial information regarding fuel use.

Analysis of recovered charcoal within archaeobotanical deposits in the region is relatively scarce compared to the analysis of waterlogged wood deposits. Gouw & Kooistra (2006) noted the comparability of what was present in the pollen spectrum and what was present in the charcoal assemblage. Charcoal analysis from a ritual deposit at Nijmegen indicated that the limit of what was available in the local environment also pervaded the socio-economic sphere. Vermeeren & Hänninen (1997) concluded that the range of taxa including oak, spruce, pine, beech and alder buckthorn was not necessarily an indication of fuel choice but use of what was locally available. It has been assumed that fuel collection was generalist rather than selective. Veal (2012) noted in a study of fuel use in Pompeii that wood selected for fuel reflected availability with a partially selective strategy. In the rural environment of the Dutch *limes* zone it was also likely that wood rather than charcoal was the preferred fuel. Veal (2012) argued that rural settlements in the Roman world were likely to have consumed more wood than charcoal compared with urbanised settlements.

More is known about the use of wood as a construction medium in the study region, primarily in military settlements. Significant analysis was undertaken by van Rijn (2004) on wood fragments recovered from Alphen aan den Rijn. Thirteen taxa were identified including alder, ash, elm, field maple, hazelnut, oak, beech and willow. These are all native species in the Netherlands and may have been locally available (see Bastiaens *et al.* (2006) for a list of native tree species in the Netherlands.). Three conifer taxa, Norway spruce, silver fir and pine, were possibly imported. Principal buildings were initially constructed from alder and ash, and subsequent buildings were constructed from poor quality oak. Wood fragments were not recovered from the military settlement of Matilo however arboreal elements have been inferred from pollen and the presence of *Neckera crispa* pollen is indicative of closed woodland located nearby (Kooistra 2005). At the rural settlement at Nieuwenhoorn, poor quality oak was also used for construction (Brinkkemper 1991). The inhabitants of Arnhem-Schuytgraaf had access to somewhat better-quality wood where large oaks have been inferred to have grown locally (Hänninen, van Rijn & Waaijen 2004). Re-use of wood at Houten-Tielland is known from the lining of wells from recycled barrel staves

which indicates a reduced availability of wood (Kooistra 1996). Conspicuously absent from wood fragments in this settlement is oak with the recovered taxa of alder and willow suggesting open woodland.

A survey of historical sources and dendrochronological evidence in the Roman world compiled by Visser (2010) showed that woodland management strategies were undertaken in the Roman world, particularly coppicing. In the Roman Netherlands, coppicing was likely to have been undertaken by the Roman army (van Rijn 2004; Lange 2010; Kooistra *et al.* 2013; van den Bos *et al.* 2014; van Dinter *et al.* 2014), and it is likely that rural settlements also undertook some form of silviculture (van Dinter *et al.* 2014, 21).

2.8. Surplus production in the Dutch Roman *limes* zone

The extent of integration of local subsistence farmers in the economy of the *limes* zone, specifically the provisioning of military and urban elements of the population was, for some time, considered minimal. Kooistra *et al.* (2013, 6) refer to an 'accepted belief that both a large part of the food as well as that of the wood for construction were imported'. Whittaker (2004) asserts, for example, that in the case of the Cananefates in the western coastal region of the Lower Rhine delta it was impossible to supply locally a large extra population and that local markets could not be relied upon. Climatic variability and the difficulty in raising productivity in the provinces could have also meant that reliance on local supply was dangerous (*ibid.*). In addition, it is also posited that imports were necessary in some regions as native farmers rarely produced the principal foodstuffs that Roman soldiers were used to and preferred. Whittaker (2004, 104) concludes that 'without imports the army could not have functioned at all in the early days of occupation since no local community could suddenly have started to produce the surpluses required to feed the troops. Other evidence is also available for imports. Two passages from Tacitus suggest importation of food (*Hist.* 4.26; *Ann.* 4.72-73). In the former, Tacitus describes a grain shortage arising from reduced shipping on the Rhine caused by drought. In the latter, Tacitus describes a tribute from the Frisii situated north of the Dutch *limes*. Mattingly (2006, 505) refers to Late Roman sources describing a fleet of 600 ships to transport grain from Britain to Rhine during the reign of Julian (Julian, *Letter to the Senate and People of Athens*, 280a; cf. Zosimus, *Historiae Nova*, 3.71 who claims 800 ships). Evidence from a grain ship at Woerden indicates emmer wheat was also imported, at least once. The presence of white-lace flower (*Orlaya grandiflora* (L.) Hoffm.) suggests a Northern Gaul origin for the grain (Willems 1986, 264; Pals & Hakbijl 1992). Further to the botanical evidence of the Woerden I ship, Willems (1986, 264) notes the existence of a dedication from Marcus Liberius, a grain trader, to the Matres Mopates (CIL XIII 8275; see also Driessen 2007), 'probably to thank them for safe arrival of a transport'. It is on this evidence of grain import that Willems (1986, 264) based his claim that 'Batavian lands were never able to provide the necessary food for all the soldiers stationed there'. The inability of the local population to supply the new inhabitants of the *limes* zone is also stated by van Es (1981) and Bloemers (1983). The arguments presented point to primitive agriculture, farmers not used to produce a surplus and an environment not capable of producing. Yet, the evidence is circumstantial and crucially, is conclusive insofar as it proves that imports occurred. The relative proportions of grain in military and urban sites show that consumption of both imported cereals and cereals that can be grown locally occurred simultaneously (see figures 2.2 & 2.3).

More recent archaeological research indicates a rural economy in which some form of surplus production was achievable. Analysis of faunal remains from the Eastern Dutch River area undertaken by Groot (2008a) from the settlements of Tiel-Passewaaij and Passewaaijse Hogeweg indicates a rural economy integrated into the Roman Empire. Whilst specialised beef production is not present, the rural economy is likely to have 'reacted to the demand of markets and perhaps

the Roman army for certain products' (Groot 2008a, 95). Analysis of settlement structure, population size, storage capacity and animal husbandry of Tiel-Passewaaij and Wijk bij Duurstede-De Horden revealed the possibility of surplus production of both animals and plants (Groot *et al.* 2009). Other research has argued for both integration of rural settlements within the macro-regional economy and the ability of the rural economy for surplus production (Roymans 2004; Heeren 2009; Vos 2009).

2.8.1. Recent modelling approaches of the local economy

In addition to methods incorporating structural, archaeobotanical, zooarchaeological and geographic evidence, landscape capacity models have also been produced to further point to hypothetical ability for surplus production. Kooistra (1996) produced a model for the Kromme Rijn region, calculating that arable land for surplus production could have been available with the available areas of streams ridges and flood basins for both high and low population estimates particularly when more grain than meat was consumed. Recently, van Dinter *et al.* (2014) have produced a landscape capacity model for the western region of the *limes* (from Katwijk to Vechten; see figure 2.1). This capacity model calculated that the local population of this region was able to produce a surplus of cereals and the region could supply sufficient wood. Animal husbandry was not limited by landscape but labour in the region, with 'implausibly large cattle herds' required to supply military and urban settlements in the region with sufficient meat (van Dinter *et al.* 2014, 32). De Kleijn *et al.* (2016, 2018) produced a further capacity model, largely based on the same assumptions used by van Dinter *et al.* (2014), reaching different conclusions. Their capacity model calculated that the availability of arable, pasture and meadow land was enough based on demand in 70 CE. For estimated demand in 140 CE, sufficient land was not available for any agricultural task to match the full demand. De Kleijn *et al.* (2016, 2018) also calculated that labour was limiting in both time periods for arable farming.

2.9. Overview

As the result of more than thirty years of intensive archaeological research, including archaeobotanical and zooarchaeological studies, substantial knowledge is available regarding the historical development of the Lower Rhine delta from the Late Iron Age to the crisis at the end of the 3rd century CE. In addition, demographic studies have attempted to reconstruct the settlement chronologies and density of the region, including a recent approach using computational modelling (Verhagen *et al.* 2016a). Palaeogeographic research has produced detailed reconstructions of the landscape (van Dinter *et al.* 2014; Groenhuijzen 2018). The diet of inhabitants and agricultural practices of native farms prior to and during Roman presence in the Lower Rhine delta have been interpreted from zooarchaeological and archaeobotanical assemblages. Farmers from the Late Iron Age onwards practiced mixed agriculture in which cattle, sheep and horse were bred alongside the cultivation of emmer wheat and barley. The arrival of the Roman army saw, perhaps, a shift to a more surplus-oriented arable farming strategy to produce food for the Roman army and inhabitants of urban settlements. Animal husbandry may have changed also whereby products were supplied by animals whilst living such as milk, manure and traction. Specialisation was largely uncharacteristic of the agriculture of the Roman period in the region. There may have been limited specialisation of beef and wool production, and horse breeding. The accumulation of interpretations from archaeobotanical and zooarchaeological assemblages has revised the previous pessimistic view of agricultural productivity in the Dutch *limes* zone. Modelling the carrying capacity of parts of the region has further revised the argument that the local population of the study region were not engaged in the supply of soldiers and inhabitants of urban settlements (e.g. Kooistra 1996; Kooistra *et al.* 2013; van Dinter *et al.* 2014; de Kleijn *et al.* 2016, 2018). Partial supply of the cereals required by

those not producing their own food was possible. Surplus production of animal products may have been less likely, not limited by land but by labour (van Dinter *et al.* 2014). Crucially, the available body of research has positively answered whether the local population could have been involved in the supply of military and civilian settlements in the Dutch Roman *limes* zone. However, there remains scope for improvement and continuation of the lines of inquiry that previous research has used. This will be discussed in the following chapter whereby the motivation for this research and the research objectives are provided.

3. Research motivation, aims and objectives

In the previous two chapters, the aims and objectives of the wider project that this study forms part of were provided as well as a synopsis of the substantial body of research that has taken place in the last thirty years within the Dutch *limes* zone. Here the motivation for this research and the specific objectives of this study will be given.

3.1. Evaluation of previous research and scope for development

Previously (chapter 2) it was noted that the large body of archaeological, archaeobotanical, zooarchaeological and palaeogeographic studies indicated that rural settlements were more integrated into the macroeconomy of the Dutch *limes* zone than previously accepted. Recent models of the carrying capacity of parts of the ancient landscape in the region have asserted the possibility that native settlements could, by the Middle Roman period, partially supply military and civilian settlements. The answer to the question “could the local population of the Lower Rhine delta supply the Roman army?” was, for Kooistra *et al.* (2013), van Dinter *et al.* (2014) and de Kleijn *et al.* (2018), yes, albeit partially. What was not tackled in significant detail, however, was how local settlements could have supplied military and civilian settlements.

The previous attempts at modelling the agricultural economy of the region via analysis of the carrying capacity of the natural landscape were static. Accordingly, there was limited scope for the inclusion of different agricultural strategies. Farmers are constantly presented with choices and decisions (Gallant 1991), and it is therefore important to model different arable, pastoral, and fuel and timber collection strategies. Different animal husbandry practices and different arable farming strategies that have been inferred from the archaeological record and different firewood strategies that are known from ethnographic studies (see e.g. Brouwer *et al.* 2007) are largely missing from earlier models. The effects on production and costs of these different possible strategies can be used to assess whether they were viable strategies to fulfil the behavioural goals of farmers in the region. Furthermore, many of the elements of the agricultural economy of the Dutch *limes* zone rely on dynamic processes. Rural labour supply and rural demand are derived from the rural population which depends on a dynamic system of household demographics. Cribb (1984, 1985, 1987) also noted the importance of understanding animal herds as dynamic systems. Stochasticity is also missing from previous static modelling approaches of the agricultural economy in the Dutch *limes* zone. Agricultural processes are often affected by random variables, however. Grain yields fluctuate annually around an average yield for example. Major life events for livestock and inhabitants of settlements such as reproduction and death also depend on a probability of occurrence. For these reasons, agent-based modelling was selected as an alternative tool to investigate the limits of the agricultural economy in the Dutch Roman *limes* zone (a further justification of the approach undertaken in this research is provided in chapter 4, section 4.1).

3.2. Research aims

In light of the above, this research contributes to previous research that has assessed the agricultural productivity of the Dutch *limes* region during the Roman period. In this research, a focus has been placed on assessing the availability of suitable land for agricultural strategies that have not yet been considered in previous landscape capacity models (Kooistra 1996; van Dinter *et al.* 2014; de Kleijn *et al.* 2016, 2018), and household labour as factors of production, or resources that can limit agricultural productivity which has only been considered briefly elsewhere. A subsequent aim of this research was to simulate agriculture in hypothetical landscapes to better understand the underlying baseline economy, as well as reconstructed

ancient landscapes, taking advantage of palaeogeographic data available from the Dutch *limes* zone. A third core aim was to explore the limiting factors on a variety of strategies within each of the agricultural activities: different strategies of arable production; different exploitation strategies of animal herds for different products, for example meat, milk, wool (from sheep) and manure (from cattle); and different strategies of fuel and timber collection such as different collection frequencies and different per capita wood consumption. Lastly, an aim of this study was to update estimated outputs of arable and pastoral production for different farming strategies that have been modelled dynamically.

3.3. Research objectives

Considering these research aims, a number of research objectives were formulated. The objectives can be divided between contributions to available archaeological methods for the study of agriculture in the past and contributions to knowledge of the limits of the agricultural economy in the Dutch Roman *limes* zone.

The main methodological objective of this research is the production of a formal, spatial dynamic model to simulate different agricultural strategies. Although for the purposes of this research, the tool developed is to be used for the study of the agricultural economy of the Dutch *limes* zone during the Late Iron Age and Roman period, it is envisaged that the agent-based model produced will be a new contribution to the archaeological toolkit. It can therefore be adapted and developed for other theoretical objectives than those listed below.

The theoretical objectives were formulated to answer some of the key questions of the “Finding the limits of the *limes*” project and to contribute new knowledge to the understanding of agriculture and its limits in the Lower Rhine delta between 12BC and 270AD. The first objective is to produce new results for the consumption demands and labour supply from rural agricultural settlements with differently-sized, dynamic populations (i). Developing from this, the second objective seeks to produce estimate land and labour costs for subsistence-based agriculture as assumed for the Late Iron Age before the development of the *limes* in the Lower Rhine delta. This includes producing new results for land and labour costs of subsistence-based arable farming as inferred from regional archaeobotanical studies; different strategies of livestock management inferred from zooarchaeological assemblages; and fuel and timber collection strategies inferred from wood macro-fossils as well as archaeological and ethnographic analogies (ii). Using these results, the limiting factors affecting the different elements within the agricultural economy can be identified and their relative impact can be gauged (iii). Although caution should be taken when estimating quantities of production in economies in the past, the results are also used to provide new estimated outputs from subsistence-based agricultural activities including grain production and the production of meat, milk, wool and manure from livestock (iv).

After simulating the baseline economy under subsistence-based agriculture and analysing the results (objectives i-iv), the subsequent objectives concern surplus-based agriculture. As with subsistence-based farming, the objectives seek to produce land and labour estimates for different agricultural tasks when different surplus-based agricultural strategies are undertaken (v). In addition, by comparing the estimated production outputs under subsistence- and surplus-based agriculture, whether changes in the agricultural economy were necessary for surplus production can be assessed (vi). Differences in the relative impact of different limiting factors between surplus-based and subsistence-based agriculture can also be gauged (vii).

Finally, by utilising the extensive palaeogeographic knowledge available for the natural landscapes of the Lower Rhine delta in the Late Iron Age and Roman periods, agriculture can be simulated in reconstructed landscapes rather than randomly-generated ones. As a result, the

reconstructed availability of different landscape elements in the study region can be assessed for its impact on agricultural productivity (viii). Furthermore, different scenarios of supply and demand in reconstructed landscapes can be estimated in order to generate new results related to the way in which local rural settlements could supply military and urban settlements in the Dutch Roman *limes* zone (ix).

4. Methodology

4.1. Introduction to agent-based modelling

Computational simulation is useful in cases when observing changes over time. Agent-based modelling enables the researcher to observe how decisions made on a micro-scale lead to macro-scale outputs. For this research therefore, agent-based modelling permits the analysis of how behaviour by settlements lead to changes in landscape use and agricultural production over time. Agent-based modelling allows for the exploration of cause and effect chains and allows for the rapid analysis of numerous “what if” scenarios (Kowarik 2012). In this sense, the agent-based model produced serves as a virtual laboratory (Premo 2006) in which scenarios that could have been and scenarios that were unlikely can be identified. The agent-based model developed for this research is exploratory but where the resolution of data permits, comparisons with data and modelling results can be made. Cause and effect chains can identify principles of equifinality, where different scenarios lead to the same outcomes, multi-finality, where different outcomes arise from the same starting conditions, and path dependency, where outcomes are an inevitable consequence of scenarios. Agricultural processes are dynamic and are affected by various fluctuations. Agent-based modelling has also been chosen to introduce stochasticity or randomness. Cause and effect chains that merge from agents’ reactions to random fluctuations can also be analysed.

Agent-based modelling is a form of computer simulation which aims at exploring how characteristics from a complex system emerge from micro-level behaviour. From its origins in the 1990s, it has become popular within multiple scientific disciplines (see Lake 2014a; Cegielski & Rogers 2016). Within archaeology, agent-based modelling has often been used to address socio-ecological dynamics, spatial processes, culture change and social interaction (Kowarik 2012). Lake (2014b) used the example of the Long House Valley model (see Dean *et al.* 2000; Axtell *et al.* 2002; Kohler *et al.* 2005) to explain features of agent-based modelling. This model focuses on the Anasazi society of the Long House Valley, Arizona from 400 CE until its abandonment in 1450 CE. In this early example of archaeological agent-based models, the researchers sought to explore the relationships between the availability of climate-determined resources, settlement location and population growth. Individual agents (households) used behavioural rules to determine where to settle in order to grow enough food to survive. When the simulation is run, the growth of a household or environmental degradation lead to settlement relocation. A settlement pattern and population size emerged from decisions made by agents which could be directly compared with archaeological data to answer questions relating to the driving forces for abandonment in the study region. The principle outcome was that climate change was not the sole reason for the abandonment of the Long House valley and the valley could continue to support small populations after abandonment. This highlighted the need to investigate other push and pull factors for abandonment.

In agent-based modelling, agents are autonomous entities that can be single (such as individual humans or animals) or collective entities (such as groups or organizations) that are able to make decisions based on their current situation following explicit behavioural rules. In the Long House model described above, the agent is a collective entity i.e. a household. Similarly, in ROMFARMS, the agent is a collective entity: a settlement. Ferber (1999) identified a number of characteristics of agents autonomy, goal-oriented, reactive and having an explicit location. Lake (2014b) also identified argued that additional features of agents that have made them more human-like and the environment, in which agents behave more realistically. For example, agents can also be capable of cognition, interacting with other agents and are capable of reproduction and adapting to a changing environment (Ferber 1999). An important axis of variation within agent-based modelling is discussed by Olševičová *et al.* (2014). The authors discussed the

differences between agent-based models that emulate and those that are exploratory. The former are complex and realistic to be used with discrete hypotheses that involve direct comparisons of data and modelling results. Models of the exploratory type do not seek to reject or accept specific hypotheses. This is related to the difference between models that test and those that generate hypotheses. Models that test hypotheses attempt to determine what happened in the past and why. Heuristic models that generate hypotheses aim to improve understanding of the processes in the past (Lake 2014a). Edmonds & Moss (2005) identified an additional axis of variations related to the approach to modelling. They distinguished between models that start with a descriptive model and are simplified when justified, and models that are made more complex only when the most simplified versions do not work. Given that ROMFARMS was developed to be an exploratory model that generates hypotheses, a descriptive model was chosen which could ultimately be used to identify where emergent phenomena could be explained through more simple models.

In recent years, several complex simulations of different agricultural economies have been produced that have simulated agriculture in the past focusing on the sustainability of different agricultural practices. Saqalli *et al.* (2014) produced conceptual models of different farming systems of the Linearbandkeramik culture of Neolithic continental Europe that can be used to test two competing theories of agricultural production: shifting cultivation and the permanent fields theory. The authors reconstructed “the functioning and quantification” of a multitude of agricultural activities within the economy of the study period: arable farming, animal husbandry, hunting, gathering and fire-wood collection. Saqalli *et al.* (2014,) argued that agent-based modelling was a suitable tool for the implementation of their conceptual model and farming systems in general as they are able to incorporate results from multiple sources. Agent-based modelling was utilised by Baum (2016) and Baum *et al.* (2016) for the analysis of agriculture among Neolithic wetland sites in Switzerland. The agent-based model developed tested hypotheses related to the highly dynamic settlement pattern. Furthermore, the model was used to test the impacts of different agricultural systems proposed for the region by combining with a model of soil nutrient cycles. The simulation model developed thus showed the potential for agent-based modelling to simulate different scenarios of arable farming practice to analyse the implications of different strategies. The ‘Social Modelling as a Tool for Understanding the Structure of Celtic Society and Cultural Changes at the End of the La Tène Period’ project developed a number of models to explore the essential aspects of one specific site: the Staré Hradisko oppidum in Czech Republic. Models of demography, agriculture and land use, and labour allocation were developed for different purposes (see e.g. Danielisová *et al.* 2015; Danielisová & Štekerová 2015; Olševičová & Danielisová 2016). Emulative models were developed to answer specific archaeological questions such as whether the workforce of the oppidum was adequate to meet production goals, or the maximum population size that could be sustained. An explorative model of land use focused on decision-making processes of farming. The models also demonstrated the usefulness of combining different computational simulation tools: cellular automata, system dynamics and agent-based modelling.

The examples provided above illustrate the current state of the art for agent-based modelling of agriculture in the past. The use of agent-based modelling enables the simulation of multiple scenarios of agricultural practice to answer specific questions where data quality permits the direct comparisons of data and modelling results, as well as explorative models designed to analyse implications of different agricultural processes and decisions. Furthermore, all three demonstrate the usefulness of combining other forms of simulation with agent-based modelling. Importantly too, the models illustrate the feasibility of simulating multi-faceted, complex economic processes to better gauge the interactions between different tasks of the agricultural economy and natural processes via agent-based modelling.

Agent-based modelling was thus chosen as an appropriate tool to answer the research questions seen as key to advancing understanding of the native economy in the Dutch *limes* zone. A focus was placed on the exploration of the availability of land and labour as limiting factors. The choice of tool (agent-based modelling) enabled an explicit analysis of the cause and effect chains of agricultural decisions made by settlements. Definitive answers related to exact mechanisms of agricultural change in the area were not sought and furthermore, as an exploratory model, validation of model results with archaeological data was only occasionally possible. But, by simulating scenarios of agricultural production, the implications of different strategies in arable farming, animal husbandry and wood collection were analysed to better understand the feasibility or sustainability of these strategies as well as reject some hypotheses. Agent-based modelling also allowed the simulation of the agricultural economy with the conditions that settlements were presenting changing every year not only as a result of decisions made in previous years but also by random events (such as deaths of settlement inhabitants or livestock) and random fluctuations in yields and outputs.

4.2. Introduction to ROMFARMS: key features

ROMFARMS is a new agent-based model developed specifically for this study using NetLogo (v. 6.0.2, Wilensky 1999), an open-source agent-based modelling environment. It can be accessed via NetLogo's Modelling Commons (http://modelingcommons.org/browse/one_model/5687). It simulates the three main agricultural activities undertaken by local rural settlements: arable farming, animal husbandry and fuel and timber collection (see figure 4.1) for an overview of the simulation order of the main processes in ROMFARMS). These activities are simulated in unison in order that ROMFARMS models agriculture as a single economic activity. It is explicitly assumed that all rural settlements in the region undertook mixed farming (Kooistra 1996, 125; Roymans 1996, 51), and also needed to collect fuel and timber alongside arable farming and animal husbandry.

ROMFARMS was developed using assumptions drawn from multiple data-sets: archaeobotanical, zooarchaeological and archaeological interpretations of assemblages within the Lower Rhine delta in the Netherlands; ancient literary sources; experimental results; and ethnographic and modern research. In some cases, however, assumptions are drawn from expert judgement and some assumptions are based on plausible estimates. The use of this range of data-sets was necessary given that no single source supplied all the required assumptions. For some elements of the agricultural economy a paucity of data or assumptions are available and for other elements, more data is available. With such a variety therefore, any modelling outputs can only be estimates although based on the currently available data.

Where possible and appropriate, ROMFARMS incorporates stochasticity. Certain life events for a settlement's inhabitants and livestock, including births, deaths and, for humans, marriage, are based a probability of occurrence. The values of some variables have random values drawn from a possible range. This reflects a more realistic scenario in which decisions made by farmers are based on fluctuating parameters. ROMFARMS is also scenario-based. Scenarios are used to simulate broader agricultural strategies via different combinations of mutable parameter values. The large number of parameters in ROMFARMS prevents a full exploration of the parameter space. ROMFARMS also records multiple outputs.

ROMFARMS has been used in this study to experiment with different agricultural behaviour of settlements to explore how land and labour could have been limiting factors. In this way, the possible mechanisms that the agrarian population of the Lower Rhine delta in the Roman

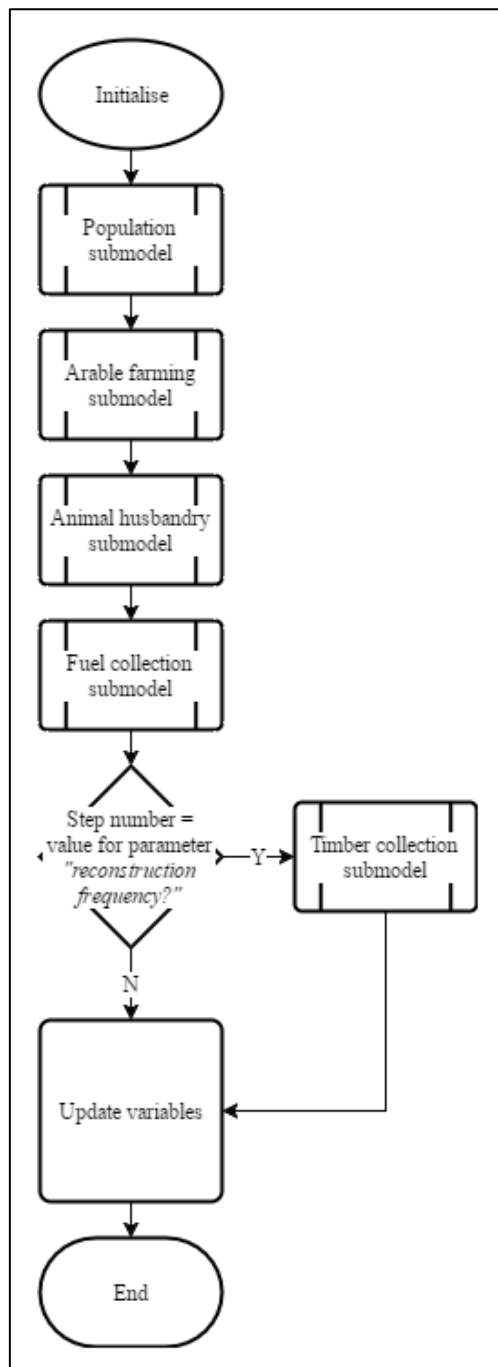


Figure 4.1. Flowchart of main processes simulated in ROMFARMS.

step representing one year, settlements undertake arable farming, animal husbandry, and fuel and timber collection. Every twenty years, settlements undertake timber collection. The number of settlements generated upon initialisation is determined by the parameters **no-1-household-settlements**, **no-2-household-settlements**, **no-3-households** and **no-5-household-settlements**. Settlements are placed randomly in the landscape on levees. Per household in each settlement, one adult male, one adult female and four individuals ranging between 0 and 15 years are generated. Settlements can also have herds of sheep, cattle and horse. At the beginning of each settlement, a herd of thirty female animals (for sheep and cattle herds) and a mix of male and female animals for horse herds is available. In ROMFARMS, the herd is the basic population unit of livestock owned by a settlement. Although it is unrealistic to assume that every settlement,

period in the Netherlands could have responded to the conquest and integration of the region into the Roman Empire.

ROMFARMS is therefore an innovative new method for the analysis of the agricultural economy in the Lower Rhine delta in the Roman period. By simulating the agricultural economy as dynamic process comprising numerous activities undertaken in each year and affected by stochastic factors, ROMFARMS departs from the static models of landscape capacity. ROMFARMS can produce therefore new results on the impact of land and labour as limiting factors on farming in the Dutch Roman *limes* zone.

4.3. Overview of sub-models: assumptions and processes

The processes, and the assumptions and their sources that these processes have been developed from are described in this section. The full list of parameters, mutable variables and immutable variables (assumptions) are provided in appendices 1, 2 and 3 respectively. Variables in ROMFARMS are provided here in *italics*, parameters are provided in **bold**. Values for variables and parameters are provided between double quotation marks.

4.3.1. Settlements

The agent in ROMFARMS is the settlement. Settlements simulated in ROMFARMS vary between single household settlements, settlements with two households, settlements with three households and settlements with five households. This is based on the estimated range of the number of households reconstructed from settlement sites in the archaeological record in the study region. One household is denoted as a married couple with any dependents (unmarried adults, children or elderly). Settlements with multiple households behave as a single agent. In each step of the simulation, with one

especially small settlements, owned herds with thirty animals in the past, herds of thirty heads have previously been cited as the minimum viable size (Gregg 1988; van Dinter *et al.* 2014). Herds with thirty heads were chosen therefore as a reasonable starting size for the initial scenarios simulated. Settlements also possess a catchment area which contains all levee cells within a 5km radius, or 10km round-trip from cell to settlement. Cells that settlements are located on are not included in a catchment area. Cells can be in the catchment areas of multiple settlements. The catchment area contains all arable land that settlements can potential use for cultivation. Meadow and pasture land located on flood-basins are excluded from a settlements catchment area as this land is considered common land and available to all settlements to use.

4.3.2. Landscape

4.3.2.1. Landscape types

ROMFARMS is a discrete patch model comprising a grid of cells with each cell representing one hectare. Each cell possesses a variable (*landscape-type*) determining whether the cell is located on flood-basin, levee or undefined. The latter is a catch-all for all land types present in reconstructions of palaeolandscapes in the Lower Rhine delta that are assumed not to have had an economic function. As a discrete patch model, a cell can have only one value for *landscape-type*. Following the reconstruction of land use by Groot & Kooistra (2009), levees can be used by settlements for habitation, arable farming and coppicing, whereas flood-basins are used by settlements for grazing and production of winter fodder for livestock.

Landscapes in ROMFARMS are either randomly-generated or based on GIS raster files of palaeogeographic reconstructions. The landscape generated is determined by the value for **region**. A value of 1-32 corresponds to a reconstructed landscape of one of 32 sub-regions that the Dutch *limes* zone has been divided into (see figure 7.1). This number of sub-regions allowed the division of the inhabited Dutch *limes* zone into equally sized areas of 10km² and avoided including the sparsely settled land between the Rhine and Meuse. A value of “hyp” for **region** generates a randomly-generated landscape. Using NetLogo’s GIS extension, cells are assigned values corresponding to a raster value. All other raster values have no *landscape-type* value. In scenarios with a randomly-generated landscape, the percentage of cells comprising levee, flood-basin and undefined landscape elements is determined by values set by the user for **area-levee** and **area-flood basin**. This allows for experimenting with different configurations. Cells can have a value for the variable *use* depending on how agents use a cell e.g. for habitation or for arable farming. The value for this *use* which defaults to “none”.

4.3.2.2. Woodland

Cells can contain woodland. If cells contain woodland, they are assigned “forest” for *use*. The percentage of the total number of levee or flood-basin cells containing wood is determined by the value **forest-cover**. The cells containing woodland are distributed randomly with the value for the cells *landscape-type* determining the quantity of wood present. This reflects a natural landscape where resources are distributed heterogeneously. Each landscape element has a mean quantity of wood with the actual quantity fluctuation around this mean within a range of $\pm 20\%$. Woodland occurring on levees is assumed to have a mean biomass of 100m³/ha and woodland occurring on flood-basins has a mean biomass of 125m³/ha (after van Dinter *et al.* 2014). Cells that are on undefined landscape elements can also contain woodland with a mean quantity of 75m³/ha (after van Dinter *et al.* 2014). The number of cells on undefined landscape elements with woodland is determined by the value for **fen-cover** and distributed randomly. Lastly, coppiced woodland can also be generated if the value of **coppicing** is “TRUE”. If coppicing is incorporated in a scenario, one cell per settlement is assigned the value “coppice” for *use*. The cells with coppiced woodland have a mean biomass of 200m³/ha (after van Dinter *et al.* 2014). Volumes of

woodland are further converted to mass in ROMFARMS as the fuel and wood requirement of agents is determined by weight. The assumed specific gravity of wood in each cell is 439kg/m³ (Zanne *et al.* 2009a; see also Chave *et al.* 2009; Zanne *et al.* 2009b). This is the specific gravity of common alder which is a prevalent species found among wood macrofossils recovered from assemblages in the Dutch *limes* zone in the Roman period (see chapter 2, section 2.7; see also van Rijn 1995, 2004; Vorst & Hänninen 2005).

Cells containing depleted woodland, provided they are not subsequently used by agents for arable land, regenerate after a period determined by the woodland type. Cells with coppiced woodland regenerate after ten years (after van Dinter *et al.* 2014, 44-45). Cells possessing natural forest regenerate after 15 years (after van Dinter *et al.* 2014). Regeneration of woodland results in complete replenishment of wood with the total quantity determined randomly using the same rules as used in the initial generation of woodland. There is no provision for partial or gradual regeneration of wood.

4.3.3. Population dynamics

4.3.3.1. Reproduction and death

A flowchart for the sub-model simulating settlement population dynamics is provided in figure 4.3 and the process is represented graphically in figure 4.4. The population of the settlements is dynamic. Growth or decline in the number of inhabitants is dependent on the probability of an inhabitant reproducing and the probability of an inhabitant dying (see figure 4.3, sub-process A for rules related to mortality in ROMFARMS). For the latter, probabilities are based on mortality values taken from Coale & Demeny's (1966) Model West Level 3 Female life table. This life table provides mortality rates for age-cohorts and is generally supposed to be valid for the Roman period (Verhagen *et al.* 2016a). In ROMFARMS, mortality rates supplied by Coale & Demeny (1966) are divided by the number of years per cohort to reflect mortality rates per year (see figure 4.2). Adult females can also reproduce once per year producing one child with an equal probability of being either male or female (see figure 4.3, sub-process B). Reproduction can only take place if a woman has a living spouse within the settlement and is between 16 and 49 years old (after Machálek *et al.* 2012, 537). The probability that an adult female can reproduce is based on fertility rates taken from Coale & Trussell (1974) (see figure 4.5). Three categories of inhabitant are used in ROMFARMS: children, adults and the elderly. Children are inhabitants from 0 to 15 years old, adults are from 16 to 49 years old, and the elderly are from 50 to 95 years old. These categories are connected to rules related to reproduction and labour. Children and elderly are not capable of reproduction but are capable of undertaking some tasks. Adults are capable of undertaking all tasks and reproduction (see section 4.3.3).

4.3.3.2. Marriage

Unmarried adults, whether those that have just reached adulthood or those whose spouse has previously died, will seek to remarry provided that there is another unmarried individual of the opposite sex (see figure 4.3, sub-process C). Marriages are patrilocal in ROMFARMS i.e. the female partner will move to the settlement of the male spouse if there is available space. Available space to the maximum number of households in a settlement: single household settlements can have a maximum of one household i.e. one married couple, whereas five household settlements can have a maximum of five households i.e. five married couples. Settlements can possess fewer households than the maximum but never more. If the number of married couples in the male spouse's settlement has already reached the maximum, marriages are matrilocal. If the number of households in both settlements has reached the maximum and maximum settlement density of the simulated landscape would not be exceeded, the new couple will establish a new settlement with the same number of households as the parent settlement. If the maximum settlement density

would be exceeded by the establishment of a new settlement, the married couple are removed from the simulation i.e. they are assumed to have migrated. From an archaeological perspective, it is of course plausible that settlements could have expanded to increase the number of households. In ROMFARMS this is not possible as the maximum number of households is immutable. This was chosen because scenarios are simulated with homogeneous occupation i.e. all agents in each scenario have the same number of households. This reduced the number of scenarios by reducing the possible combinations of parameters.

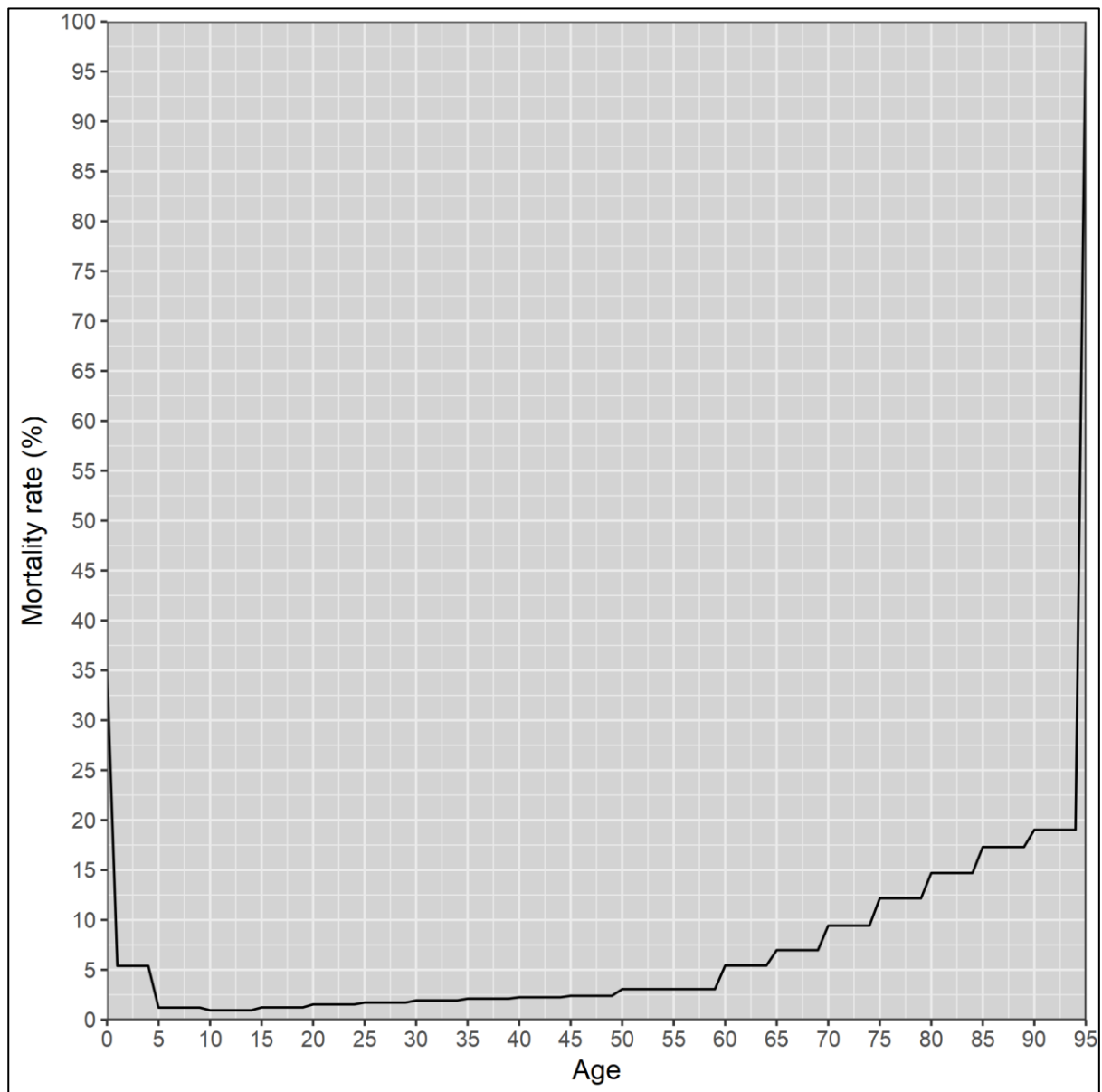


Figure 4.2. Probability of death for inhabitants of settlements per age of inhabitant (mortality rates from Coale & Demeny 1966).

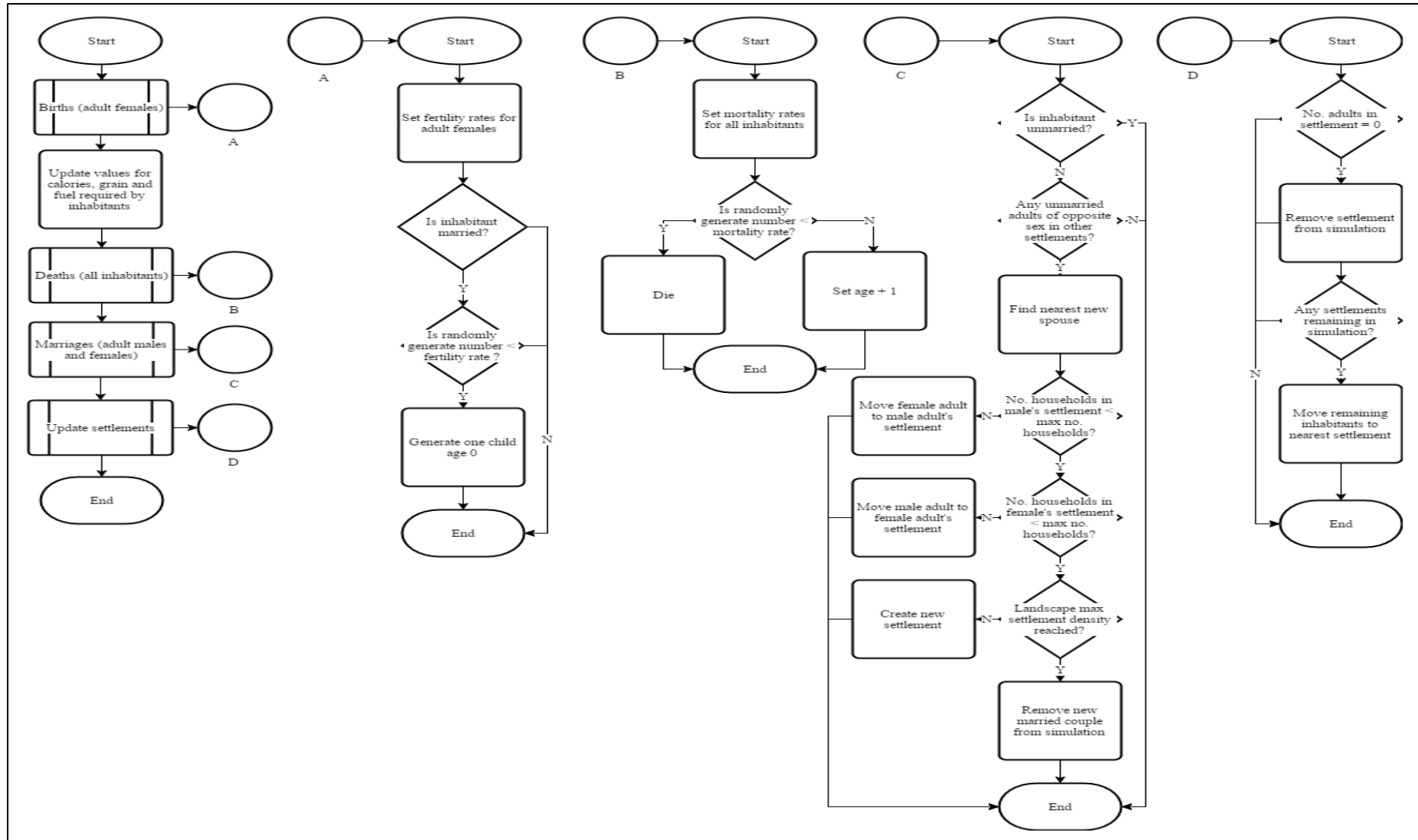


Figure 4.3. Flowchart of population sub-model that simulates settlement population dynamics.

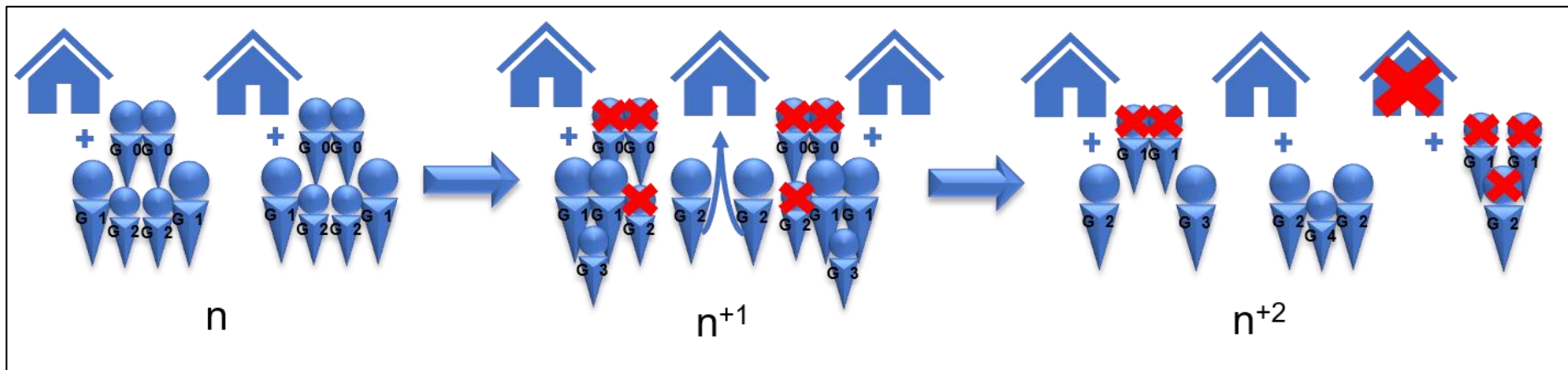


Figure 4.4. Graphic representation of settlement demography showing how marriages can generate new settlements and the deaths of inhabitants can lead to the removal of a settlement.

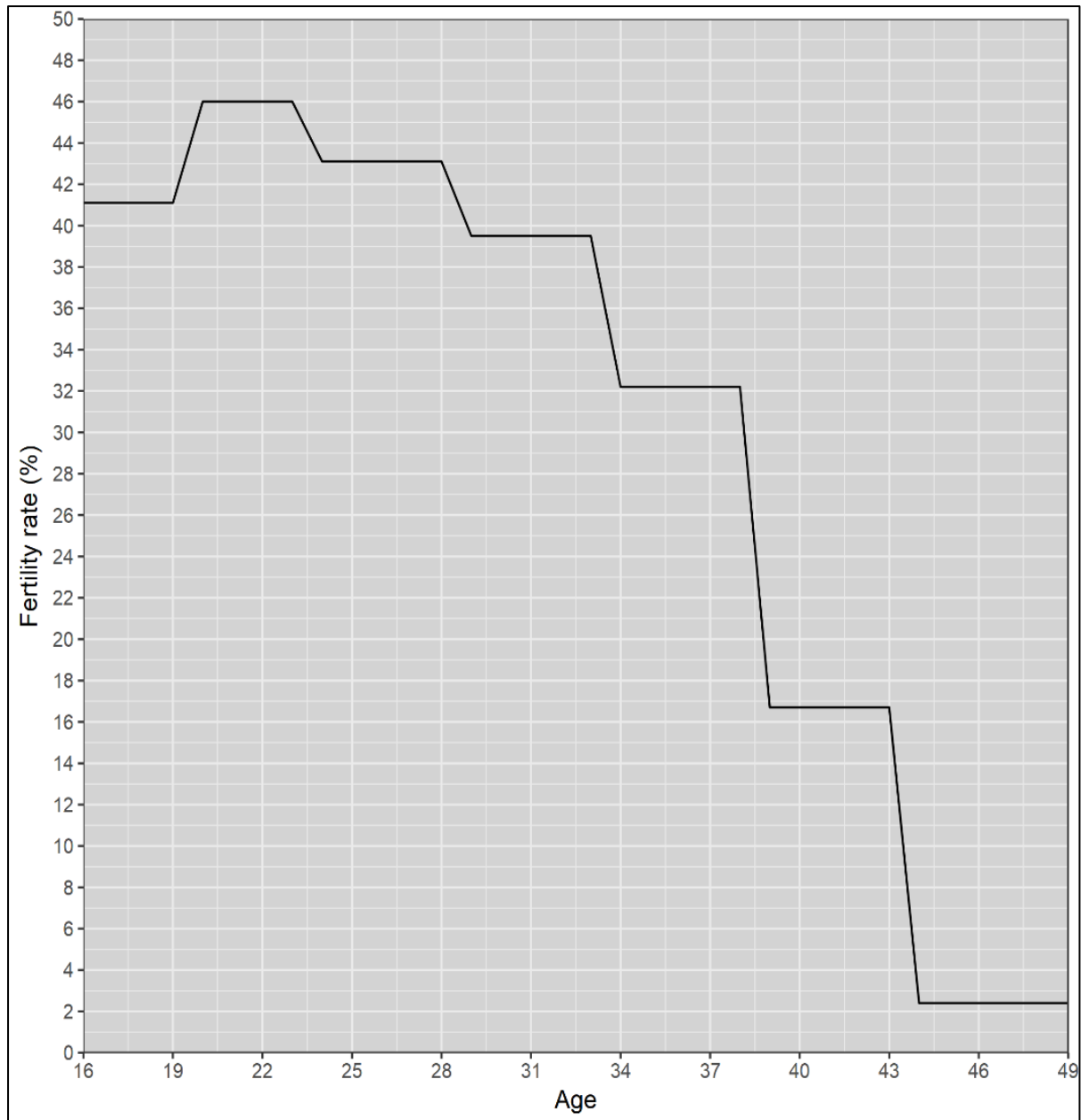


Figure 4.5. Probability of married adult females producing one offspring per age of married adult female (fertility rates from Coale & Trussell 1974).

4.3.3.3. “Strong” and “weak” workforces

The inhabitants of settlements are the sole source of labour available to each settlement in ROMFARMS. There is no provision for communal or collective labour among settlements in ROMFARMS although it is acknowledged that there was undoubtedly a role for this in the past (see chapter 8, section 8.4.2 for a discussion for further development of ROMFARMS). The age of inhabitants determines what agricultural activities can be undertaken. Children from 10 to 15 and the elderly comprise the weak workforce and can undertake fuel collection. All adults comprise the strong workforce and can undertake all other activities. The separation of strong and weak workforces follows the assumptions made by Machálek *et al.* (2012) and Danielisová &

Štekerová (2015, 174). Settlements that do not have any adult males or females, whether married or not, are removed as only adults can perform the main food-producing tasks. Any remaining children in the settlement are sent to the nearest extant settlement. The position of orphans and other dependents in rural settlements is largely missing from the archaeological and historical record. However, Dyson (2011, 437) suggested that orphans may have been taken in by other families in the Roman countryside. Furthermore, Saller (2011, 119) wrote that ‘households took in needy relatives beyond the nuclear family’. Relocating orphans and other dependents to other settlements prevents their premature removal from the simulation and there is a historical basis for this assumption.

4.3.3.4. Calories required

At the beginning of the population dynamics sub-model each year the requirements of settlements are updated to reflect population changes that had occurred in the previous year. The annual calorific requirement for humans differs according to age and sex of inhabitants and are given in table 4.1. The assumptions are taken from Gregg (1988) with some estimates updated using FAO estimates (2004). It is assumed that infants suckled in the first year of life and required no calories from plant or animal products. For children between 1 and 5 of either sex, 1360kCal is required per day. For children between 5 and 10 years, it is assumed that the daily requirement is 2010 kCal. For children aged 10 to 15 it is assumed that the daily requirement for male individuals is 2750 kCal and for female individuals is 2420 kCal. The estimated calories required by adults provided in previous studies depend on the lifestyle led. It has been assumed that agriculturalists led moderately active lifestyles with periods of intense activity. Therefore, it is assumed that adult males require 3000 kCal each per day with 550kCal extra required for six labour intensive periods when harvesting, ploughing and sowing are undertaken. The calories required by adult women are less: 2800 kCal per day with an extra requirement of 400 kCal for six weeks. Adult women with a suckling child require more additional calories: a lactating female will require 675 kCal extra per day. Gregg (1988) does not account for the calorific requirement of the elderly however in ROMFARMS a distinction is made using data from FAO (2004). Men older than 49 years require 2650 kCal per day and women older than 49 years require 2450 kCal per day. Each individual also has a requirement for fuel although this is assumed to be constant for all ages and sex. The daily per capita consumption is dependent on the value for the parameter **daily-per-capita-fuel-use**.

SEX	AGE	ANNUAL KCAL X 10 ³ REQUIRED
MALE	0	0.00
	1-4	496.40
	5-9	733.65
	10-15	1003.75
	16-49	1118.10
	50+	967.25
FEMALE	0	0.00
	1-4	496.40
	5-9	733.65
	10-15	883.30
	16-49	1038.80
	16-49 (lactating)	1285.18
	50+	894.25

Table 4.1. Annual calories (kCal x 10³) required by individuals. Data from Gregg (1988) and FAO (2004).

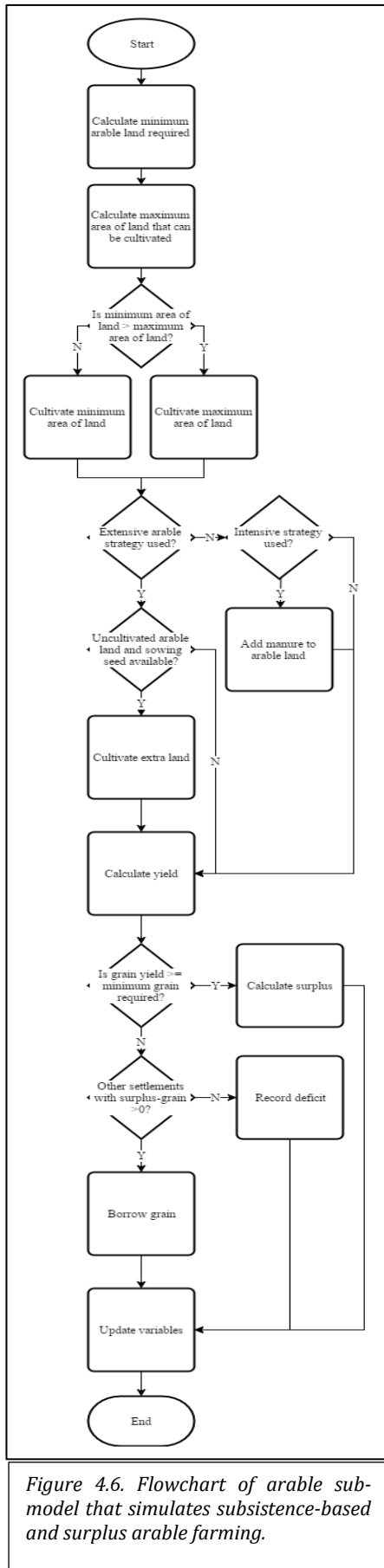


Figure 4.6. Flowchart of arable sub-model that simulates subsistence-based and surplus arable farming.

4.3.4. Arable farming

In each step of the simulation settlements undertake arable farming as part of a mixed agricultural economy. An overview of the arable farming sub-model is provided in figure 4.6.

4.3.4.1. Calculating grain required

Primarily, grain is produced to meet the demands of the settlements' inhabitants. The quantity of grain needed for consumption by the inhabitants of the settlements is calculated according to the calories required by the inhabitants of the settlement, the proportion of calories derived from crops and the calorific content of grain:

$$1) g = x \frac{cp}{z} + s,$$

where g is the total grain required (kg), c is the total calories required by all inhabitants of a settlement, p is the percentage of calories derived from crops and z is the calorific content in 1kg of grain, x is proportion of extra grain required to be cultivated and s is the sowing-seed required for the following year. s is calculated as:

$$2) s = r \left(\frac{cpzx}{y} \right),$$

where r is the sowing rate (kg/ha) and y is the mean basic of grain per hectare. c is calculated as:

$$3) c = t \sum (n_{cat} c_{cat}),$$

where t is the length of one year in days, n is the number of inhabitants per age category ($_{cat}$) and c is the calories required per day per inhabitant per category ($_{cat}$).

The calorific content of cereal grain in ROMFARMS is estimated as a constant 3100 kCal/kg (after Kooistra 1996, 67; van Dinter *et al.* 2014, 45, 49). A mean basic yield per hectare is assumed for grain at 1000kg/ha (ibid.). The sowing rate of grain is estimated as 200kg/ha for broadcast sowing (ibid.). Broadcast sowing has been assumed in light of Kooistra's (1996, 68) argument that row-sowing did not confer any significant advantage except in times of grain shortage. (1996, 68). Gregg (1988, 74, table 3) assumed a standard deviation of 189kg for a basic yield of 1054kg/ha for winter-sown emmer or spelt wheat based on data from the Statistisch-Topografisches Bureau between 1850-1905. In ROMFARMS the mean basic yield fluctuates each year within a range $\pm 20\%$. The cycle of primary macronutrients (nitrogen, potassium, phosphorous etc.) in soil is not simulated in ROMFARMS. The complexity of simulating these cycles has precluded their inclusion. Following the

arguments of Gregg (1988; after Loomis 1978; see also Hall 1917; Cooke 1976; Johnston & Mattingly 1976) however, low yields in the past may have resulted in relatively stable levels of macronutrients. Settlements in ROMFARMS can cultivate a small surplus to serve as a buffer in bad-years. Whilst assumed to have been cultivated in the past (see e.g. Halstead & O'Shea 1989; Groot & Lentjes 2013), the size of the buffer has been debated. The size of the buffer depends on the value for the parameter **store-size**.

4.3.4.2. Calculating arable land required

After calculating the minimum quantity of grain required for consumption, settlements calculate the area of arable land to be cultivated to produce this quantity of grain as follows (see figure 4.7):

$$4) a = \frac{g}{y},$$

where g is the total quantity of grain (kg) required by settlements as calculated in equation 1 and y is the mean basic yield/ha of grain.

For each settlement the maximum area of land that can be cultivated is calculated. This is the maximum area available within a settlement's catchment area, the maximum area that can be sown with available sowing seed or the maximum area that can be cultivated by a settlement's available labour, whichever is lower. If the minimum area of land to be cultivated is less than or equal to the maximum area of land that can be cultivated, settlements cultivate the minimum area of land necessary to produce enough grain for consumption. Otherwise settlements cultivate the maximum area of land that can be cultivated with available resources (land, labour or sowing-seed).

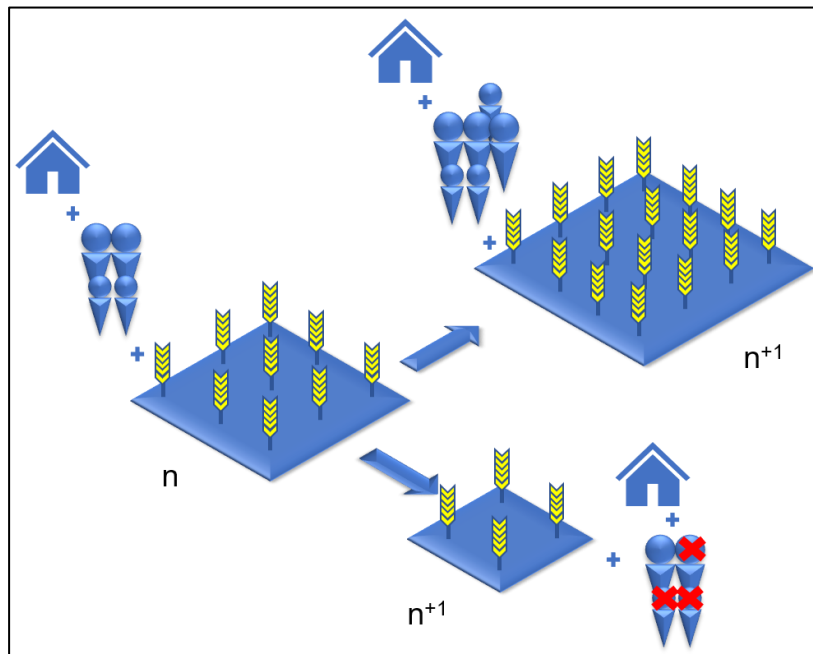
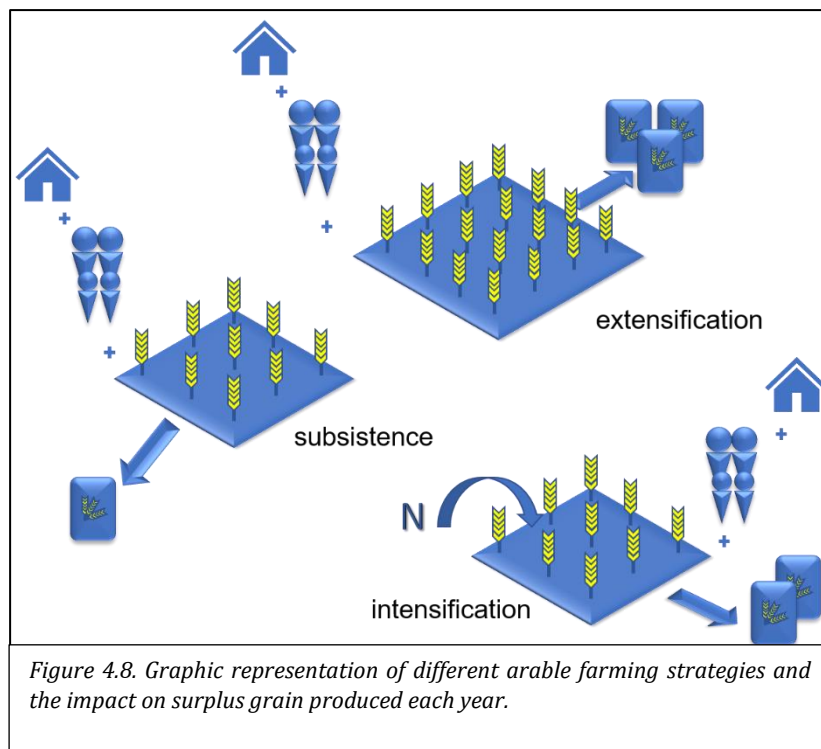


Figure 4.7. Graphic representation of subsistence-based arable farming showing how increases and decreases in settlement populations from yearⁿ to yearⁿ⁺¹ increase and decrease the size of arable farms.

4.3.4.3. Calculating arable land to be cultivated

It was noted in the previous chapter (section 3.1) that arable farming in previous models of carrying capacity was treated as a static activity with constant yields and no variety in the arable strategy employed. ROMFARMS simulates different arable strategies. Groot & Lentjes (2013) note

two main methods of switching from subsistence to surplus production: agricultural expansion and agricultural rationalisation. The former is further divided into extensification (i.e. “by increasing units” of production) and intensification (i.e. “by increasing yield per unit”) (ibid., 12-13). Agricultural rationalisation concerns greater organisation of agricultural land or specialisation. There is a general lack of evidence from archaeobotanical and zooarchaeological remains for specialisation in the Dutch *limes* zone (see chapter 2). Furthermore, the difficulties encountered when modelling socio-cultural behaviours (see section 8.4.1) meant that agricultural rationalisation had to be omitted from ROMFARMS. In ROMFARMS, the most important decisions available to farmers have been compiled into three main strategies: subsistence-based arable farming, extensive arable farming, and intensive arable farming (see figure 4.8). The strategy employed is determined by the value for the parameter **arable-strategy**. Under subsistence-based and intensive arable farming, settlements cultivate only the area of land as calculated in equation 4. If settlements undertake an extensive farming strategy, extra land is cultivated provided that sufficient labour, land and sowing-seed is available. The area of extra arable land that is cultivated is the maximum area of land that is available, the maximum area of land that can be cultivated by the settlement’s labour force or the maximum area of land that can be sown by the available surplus grain, whichever is lower. If settlements undertake an intensive farming strategy, extra land is not cultivated however settlements incorporate manure into arable land to be cultivated. The maximum amount of manure that can be incorporated is limited to the optimum application. The optimum application of manure is assumed to be 10×10^3 kg. If the quantity of manure available to a settlement is less than the required quantity needed for optimum application, manure is divided equally per hectare of land to be cultivated. The cells containing arable land that settlements will cultivate are the nearest cells within a settlement’s catchment area. Settlements value the availability of arable land over the preservation of naturally occurring woodland. As discussed earlier (chapter 2 section 2.4), even prior to Roman period the Dutch *limes* zone had been largely deforested indicating that land for farming or habitation took precedence. Therefore, if the land that settlements wish to cultivate contains woodland, settlements will deforest the area and collect any wood present for their own uses.



4.3.4.4. Calculating grain yield

Once the total area of land to be cultivated by settlements is calculated, for each settlement the grain yield harvested is calculated:

$$5) g = p(ay + e),$$

where g is the total grain yield (kg), p is the randomly generated percentage increase or decrease of the mean basic yield each step within the range $\pm 20\%$, a is the total area of arable land cultivated, y is the mean basic yield of grain per hectare, and e is the extra grain yield due to the application of manure if an intensive arable strategy is undertaken. e is calculated:

$$6) e = adni,$$

where e is the quantity of extra grain (kg), a is the total area of arable land cultivated, d is the quantity of manure incorporated per hectare of arable land, n is the nitrogen content per kg of manure and i is the quantity of extra grain produced per kg of nitrogen.

The increase in yield due to manure application is 15kg of grain per 1kg of extra nitrogen (Shiel 2012, 20). Per 1000 kg of manure, farmyard manure (FYM) contains 6×10^{-3} kg of nitrogen (Chambers *et al.* 2001, 6 table 1). If the total grain yield is more than the total grain required by settlements, the quantity of extra grain is stored for one year by settlements as surplus grain. If the total grain yield is less than the total grain required by settlements, settlements will borrow grain from the nearest settlement with surplus grain. If there are no settlements with surplus grain, settlements will record a deficit if the total grain yield is less than the total grain required.

4.3.4.5. Calculating labour required

The total number of hours required by settlements to produce grain is calculated from the total area of land cultivated, the labour requirement per activity within arable farming and the size of the workforce:

$$7) l = \frac{\sum(ah_{task})}{n},$$

where l is the total number of hours required for arable farming, a is the area of arable land cultivated, h is the number of hours per hectare of cultivated land per task ($_{task}$) and n is the number of adult males and females in a settlement.

TASK	HOURS	NOTES
PLOUGHING	30	per ha
SOWING	3	per ha
HARVESTING	24	per ha
MANURING	30	per ha
FODDER PRODUCTION	16	per ha
FUEL COLLECTION	3	per trip
TIMBER COLLECTION	6	per trip

Table 4.2. Hours required per agricultural task.

Arable activities in ROMFARMS have been assumed to be ploughing, sowing, harvesting and manuring (when settlements undertake intensive arable farming). Steensberg (1979) and Reynolds (1987) assume one hectare can be ploughed in 2.5 days (cf. Hansen 1969 who assumed

1ha could be ploughed in twenty hours based on experiments with a replica ard plough and two oxen). In ROMFARMS, one working day is assumed to be twelve hours and therefore ploughing one hectare of land takes thirty hours. For sowing, one hectare of arable land can be broadcast-sown in 0.25 days (after Sigaut 1992) and therefore three hours in ROMFARMS. It is assumed also that one adult can harvest 3.5ha of arable land within two weeks (after van Dinter *et al.* 2014, 49; see also Gregg 1988, 161-162), therefore harvesting one hectare takes 48 hours. There are no estimations for the hours required to apply manure to one hectare of land in past agriculture. Therefore, it is estimated that manure application took the same amount of time as ploughing i.e. thirty hours per hectare. This is, unfortunately, only a best-guess. Labour estimates for agricultural tasks are provided in table 4.2.

4.3.4.6. Fallowing

If settlements undertake a subsistence-based or extensive arable strategy land cultivated in one year must be left fallow the following year. The length of fallow depends on the value for the parameter “*fallow-time*”. A value of two for this parameter relates to biennial fallow; a value of three relates to triennial fallow, and so on. Under an intensive arable strategy, fallowing is not necessary owing to the beneficial effects of incorporating manure into arable soil.

4.3.5. Animal husbandry

Animal husbandry in ROMFARMS is simulated via a systems dynamics model of animal herds. System dynamics is another form of modelling that uses stocks and flows. In the case of animal herds, an initial population of animals (stock) can increase and decrease as a result of births and deaths (flows). Births increase the stock and deaths decrease the stock. Whether an animal is born or dies is determined by probability rather than as a result of decisions made by the animals themselves. In the subsequent steps, the remaining population at the end of the last step becomes the new stock. The sub-model of animal husbandry is depicted in a flowchart in figure 4.9. Settlements own herds of sheep, cattle and horse.

4.3.5.1. Setting slaughter rates

ROMFARMS simulates different exploitation strategies of animals for different products that have been inferred from zooarchaeological assemblages in the region (see chapter 2, section 2.6.4). Different strategies of herd management to exploit livestock for a particular product are simulated through the combination of different slaughter rates for the different age categories of livestock. The age categories of animals are provided in table 4.4. Slaughter rates are derived from an earlier systems dynamics model by Joyce & Verhagen (2016) and also provided in table 4.3. Horse herds are simulated differently. It is assumed that maximising the number of immature horses that can be removed from a horse herd without causing the extinction of the herd was the behavioural goal for horse husbandry. Therefore, in place of a slaughter rate, ROMFARMS utilises an optimum removal rate which is also provided in table 4.3. Slaughter or removal rates result in the highest yields of the product to be exploited whilst preventing extinction of the herd. Slaughter rates are set at the beginning of each year depending on the value for parameters **cattle-strategy** and **sheep-strategy** (only one strategy for horse breeding is assumed in ROMFARMS).

ROMFARMS simulates only a limited number of herd management strategies because the large number of combinations of slaughter rates means it is not practical to simulate all possible combinations. The exploitation strategies simulated by ROMFARMS are only a small number of the possible ways that livestock could be managed. Different combinations of slaughter rates may result in different product outputs. Equifinality means also that the same product outputs could emerge from different combinations of slaughter rates than those simulated in ROMFARMS. The

implementation of more exploitation strategies has been identified as a possible area for further development of ROMFARMS (see chapter 8, section 8.3.5.2).

ANIMAL	AGE CATEGORY	EXPLOITATION STRATEGY	MORTALITY RATE (REMOVAL RATE) (%)
SHEEP	Young	Meat	1.00
		Milk	44.00
		Wool	10.00
	Immature	Meat	45.00
		Milk	1.00
		Wool	20.00
	Adult	Meat	1.00
		Milk	1.00
		Wool	10.00
CATTLE	Young	Meat	1.00
		Milk	50.00
		Manure/traction	20.00
	Immature	Meat	45.00
		Milk	1.00
		Manure/traction	0.00
	Adult	Meat	1.00
		Milk	8.00
		Manure/traction	20.00
HORSE	Young	-	0.00
	Immature	-	55.00
	Adult	-	0.00

Table 4.3. Mortality rates of young, immature and adult cattle per exploitation strategy; removal rates of young, immature and adult horse. Rates adapted from Joyce & Verhagen (2016).

ANIMAL	AGE CATEGORY	MINIMUM AGE (YEARS)
SHEEP	Young	0
	Immature	1
	Adult	2
CATTLE	Young	0
	Immature	1
	Adult	3
HORSE	Young	0
	Immature	1
	Adult	4

Table 4.4. Minimum ages per age category of the three livestock species in ROMFARMS.

4.3.5.2. Reproduction

After slaughter rates are set, adult female animals reproduce. Fertility rates of animals are set as probabilities of producing offspring. Fertility rates differ depending on animal species. Adult female sheep have an 80% probability of producing at least one offspring and a further 20% probability of producing two offspring. Adult cattle and horses can only produce one offspring with a probability of 70% or 60% respectively. These fertility rates are best guesses, however. If an adult sheep or cow produces offspring in one year, they are denoted as adults for the

remainder of the year. The adult and its offspring are linked until the offspring mature to the immature age category or if the offspring die or are slaughtered. Lactating animals with dead or slaughtered offspring continue to produce milk for the remainder of the year.

4.3.5.3. Natural mortality

After reproduction, neonatal mortality is simulated. Newborn sheep have a probability of 32% of dying before the first year, and cattle and horse have a probability of 20% (after Gregg 1988, 104,113; see also Perry 1984). Subsequently, a process simulating natural mortality occurs. This process is taken from an individual-based model of Konik horse populations by Galic (2014). At birth, each animal is assigned a random value between 0 and 1 reflecting life expectancy at birth. An animal dies when the value generated by a survivorship function exceeds the randomly generated value. The value generated by the survivorship function is calculated as:

$$8) s = -1\mu a - e^{(-1\alpha_m \alpha_s)} e^{\left(\left(\frac{a}{\alpha_\sigma}\right)^{-1}\right)},$$

where s is the survivorship value, μ is the annual mortality rate, a is the age of the animal, α_m is the modal age senescence of the animal species and α_σ is the standard deviation in the age of senescence.

This value is recalculated each year for each animal. For sheep, the age of senescence is assumed to be 7.5 years, for cattle it is assumed to be 17.5 and for horse it is 27.5. These assumptions are also best guesses. Standard deviation from this modal age of senescence is 2.5 years for all animal species. Background mortality is the same as used by Galic (2014) for Konik horse populations in the Netherlands and is the probability each year of an animal dying due to natural causes. Modern herds of Konik horse live in similar environments to animals living in parts of the Dutch *limes* zone during the Roman period and provide suitable analogous data for mortality. The same mortality, for want of other detailed data, is assumed to be the same for cattle, sheep and horses in this model. The background annual mortality rate is assumed to be 1.4% (after Galic 2014).

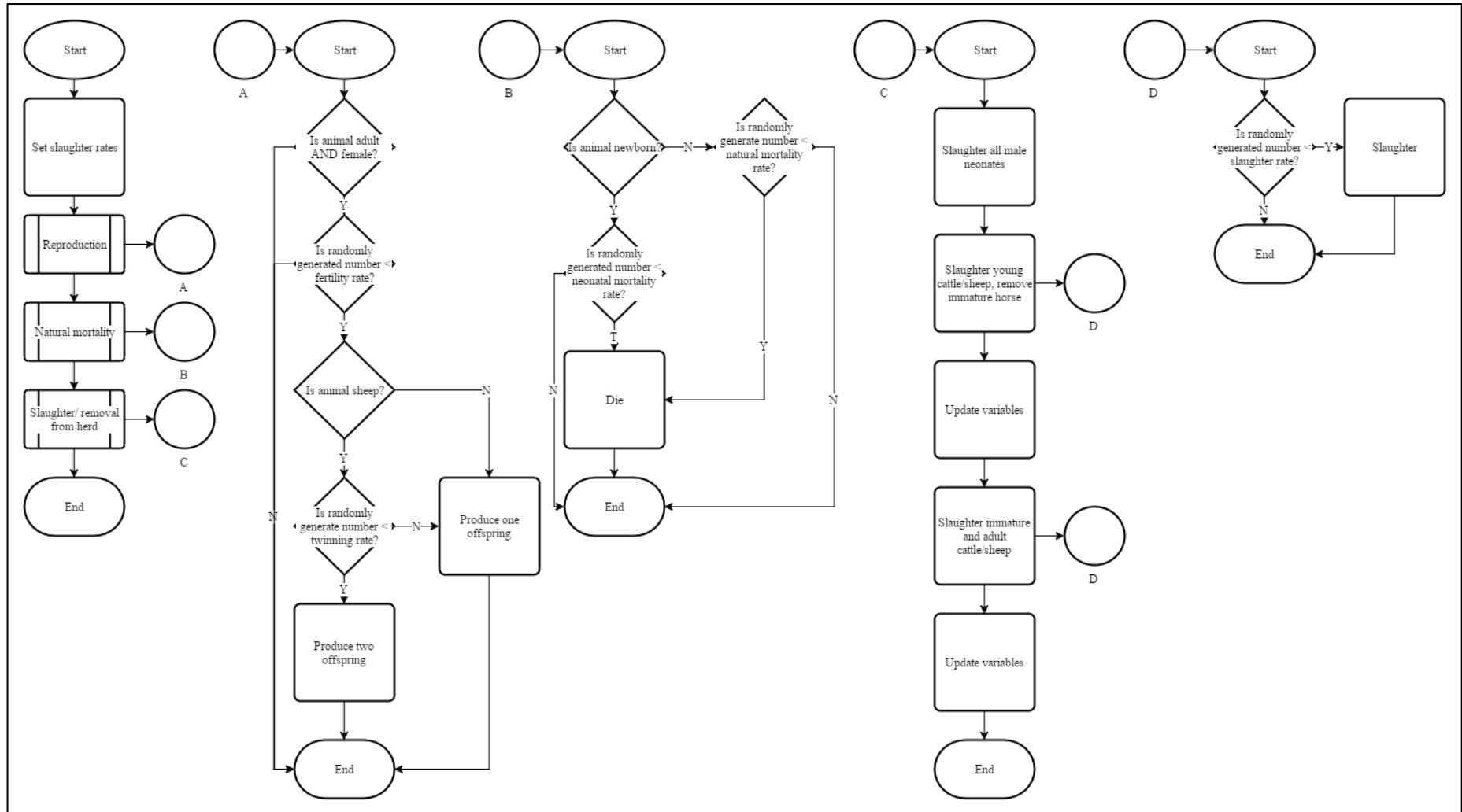


Figure 4.9. Flowchart of animal husbandry sub-model that simulates management and exploitation of sheep, cattle and horse herds.

4.3.5.4. Slaughter

After natural mortality occurs, settlements will slaughter animals (or in the case of horse, remove immature animals from the herd). As mentioned above, slaughter rates are probabilities of an animal dying with slaughter rates different for different ages and species of animals which depend on the exploitation strategy a settlement is employing. Animals are slaughtered at different times, however. Any remaining neonatal male sheep or cattle are immediately slaughtered and remaining female sheep or cattle are promoted to the young category. Young sheep or cattle are slaughtered at the beginning of the process to maximise milk production and immature horse are removed from the herd at this point too. Some variables are updated after this initial slaughtering including the area of pasture land required by herds, the milk yield from sheep and cattle herds, and the yield of wool from sheep herds. Immature and adult sheep and cattle are subsequently slaughtered and further variables are updated: the yield of meat from cattle and sheep herds, the yield of manure from cattle herds, the area of meadow land required to produce winter fodder for all herds and the labour required to produce this fodder.

4.3.5.5. Calculating pasture and meadow land required

Farmers in ROMFARMS engage in extensive animal husbandry i.e. animals are kept outside of the settlement in pasture land for the majority of the year which reflects zooarchaeological evidence from the Dutch *limes* region (see e.g. Groot 2008a, Groot & Kooistra 2009). It is assumed, however, that cattle were wintered inside with manure being available for collection at this point. Byrehouses with space for livestock and phosphate staining indicative of animals being kept in them are typical of the eastern part of the study region (see Heeren 2006, 2009; Groot & Kooistra 2009), and the presence of very young cattle remains within some settlement contexts indicated that cattle were kept near the settlement for at least part of the year (see e.g. Groot 2008a; Groot & Kooistra 2009). For sheep and horses, the lack of young animals within settlements suggest permanent pasturing outside the settlement. Pasture land was likely to have been in the flood basins in the region which supplied grassland (see chapter 2 section 2.4). Given that ROMFARMS assumes extensive animal husbandry, it is assumed that animals were in pasture on grassland in flood basins for 8 months. For the remaining four months of the year, fodder is supplied to animals when food is scarce (see below). Gregg (1988, 118; after Netting 1968, cited in *ibid.*) assumed that the area of pasture land required for ten sheep would have been the same as required for one cow. Brinkkemper (1993, 131) however assumes the requirement of three adult sheep is the equivalent of one cow. Given that Brinkkemper's study corresponds more closely to the region and period in this research, it is assumed therefore that the land requirement of one adult sheep is one third that of a cow (see table 4.5 for estimates of land required by sheep, cattle and horse). As it is assumed that one hectare of grassland can support three adult cattle (after van Dinter *et al.* 2014, 46-47), in ROMFARMS one hectare of grassland can support nine adult sheep, therefore. For horses, the required area of pasture-land for one adult horse is the same as one adult cow in this simulation (after Kooistra 1996, 72; Woltering 2000). The pasture land required by animals given above is for adult animals. Younger animals are assumed to require smaller areas of land. It is assumed therefore that the pasture-land required by an immature animal (see above for age categories of animals) is 80% of the requirement of their adult equivalent and young animals required 15% of the requirement of their adult equivalent (after Netting 1981, 39; Gregg 1988, 107, 118; van Dinter *et al.* 2014, 47).

ANIMAL	AGE CATEGORY	PASTURE LAND REQUIRED (HA)	MEADOW LAND REQUIRED (HA)
SHEEP	Young	0.017	0.0126
	Immature	0.089	0.0672
	Adult	0.111	0.084
CATTLE	Young	0.05	0.0378
	Immature	0.27	0.2016
	Adult	0.33	0.252
HORSE	Young	0.05	0.0378
	Immature	0.27	0.2016
	Adult	0.33	0.252

Table 4.5. Area of pasture and meadow land required (ha) by young, immature and adult sheep, cattle and horse. See appendix 3 for sources of assumptions.

4.3.5.6. Calculating labour required

For all animals, the scarcity of food during winter, which is assumed to be four months in ROMFARMS, would have required settlements to supply fodder to herds (van Wijngaarden-Bakker 1988). It is assumed that an adult cow requires 756kg for the four-month winter period simulated in ROMFARMS (van Dinter *et al.* 2014, 47; see also Groenmann-van Waateringe & van Wijngaarden-Bakker 1987). This corresponds also to the requirement assumed by Brinkkemper (1991, 129) for Iron Age cattle on Voorne-Putten. The fodder requirement for horse is assumed to be the same because the area of pasture land required by an adult cow or horse is also assumed to be the same. It is assumed that the requirement for one adult sheep's fodder for four months is one third of that assumed for a cow: 252kg. As with the area of pasture land required, the fodder quantity required by animals is reduced according to the age category of animals: immature animals require 80% of adult animals and young animals require 15% of adult animals. Van Dinter *et al.* (2014, 47) assumed a yield of 3400kg of hay per hectare of grassland. This is assumed to be an optimum yield, however. In ROMFARMS, a sub-optimum yield is assumed: 3000kg per hectare (after Kreuz 1995, 81).

The total quantity of fodder required by animals is calculated as follows:

$$9) f = \sum (n_{spcat} f_{spcat}),$$

where f is the total quantity of fodder required by all animals (kg), n is the number of heads per species (sp) per age category (cat) and f is the fodder required per head per species (sp) per age category (cat).

The total area of pasture and meadow land required by animals is calculated as follows:

$$10) a_p = \sum (n_{spcat} a_{spcat})$$

$$11) a_m = \frac{f}{y}$$

where a_p is the total area of pasture land required by all animals (ha), a_m is the total area of meadow land required by all animals (ha), n is the number of heads per species (sp) per age category (cat), a is the area of land required per head per species (sp) per age category (cat), f is the total fodder required by all animals as calculated in equation 9 and y is the yield of fodder per hectare.

The labour required to produce sufficient fodder is calculated as:

$$12) l = a_m h,$$

where l is the total number of hours required to produce fodder for all animals, a_m is the area of meadow land required to produce fodder as calculated in equation 11 and h is the number of hours required to mow one hectare of meadow land.

No assumptions were available for the time taken to mow one hectare of meadow land. It was estimated that mowing was faster than harvesting, however. In ROMFARMS the length of time required to mow one hectare of meadow land is estimated to be sixteen hours (see table 4.2).

4.3.5.7. Calculating yields

ROMFARMS estimates the yields of various animal products from herds based on the number of slaughtered and living animals each year. The quantity of meat available is calculated by the proportion of the live weight of the slaughtered animal available for consumption. The live weight of animals differs per species and per age category. The total meat yield for sheep and cattle is calculated as:

$$13) m_1 = \sum (n_{sp_{cat}} y_{sp_{cat}}),$$

where m_1 is the total meat yield from all animals (kg), n is the number of heads per species ($_{sp}$) per age category ($_{cat}$) and y is the yield of meat per species ($_{sp}$) per age category ($_{cat}$) (kg).

An adult cow is assumed to have a live weight of 200kg (van Dinter *et al.* 2014, 46; see also IJzereef 1981; Reichstein 1984; Prummel 1992; Brinkkemper 1991). Immature cattle are assumed to have a smaller live weight of 150kg i.e. 75% of an adult cow (van Dinter *et al.* 2014, 46). Gregg (1988, 105) supposes a weight of 75kg for young cattle in the Neolithic however the weight of an adult animal is assumed to be higher at 550kg for an adult cow. Therefore, a calf is assumed to have a live weight of 35kg (van Dinter *et al.* 2014, 45; see also IJzereef 1981). The live weight of an animal is not, however, the weight of meat available. Van Dinter *et al.* (2014, 46) assume that 60% of the live weight of cattle is available for consumption. Sheep provide much smaller yields of meat. An adult sheep has an assumed live weight of 25kg (after IJzereef 1981; see also Gregg 1988, 116) and an immature sheep weighs 18.75kg (after van Dinter *et al.* 2014, 46). A young sheep is assumed by Brinkkemper (1993, 130) to yield 30% of the calories of an adult sheep but it is not explicitly stated by Brinkkemper that young sheep weigh 30% of an adult animal. It is assumed therefore that a young sheep weighs 10kg (after Gregg 1988, 116). A sheep carcass is assumed to be 30% of an animal's live weight (after IJzereef 1988). The meat yields per animal per age category are provided in table 4.6.

The total quantity of milk from cattle and sheep is calculated as:

$$14) m_2 = \sum (t_{sp} y_{sp} (\frac{n_{1_{sp}}}{2} + n_{2_{sp}})),$$

where m_2 is the total milk yield, t is the total length of lactation per species ($_{sp}$), y is the daily milk yield (l) per species ($_{sp}$), n_1 is the number of heads of lactating animals with surviving offspring per species ($_{sp}$) and n_2 is the number of heads of animals with no surviving offspring per species ($_{sp}$).

Milk is only available from post-parturient adult animals for a limited period each year. The quantity of milk available is reduced if young animals are also suckling. Gregg (1988, 106; Dyson-Hudson & Dyson-Hudson 1970 cited in *ibid.*) assumes that only half of the cattle with surviving suckling offspring would produce surplus milk for human consumption. Therefore, the

number of adult lactating animals with surviving suckling offspring is reduced by half to reflect this assumption. Cattle lactate for 200 days in ROMFARMS (after Gregg 1988, 106) and sheep lactate for 135 days (after Gregg 1988, 116; see also Redding 1981). Daily milk offtake for cattle among Maasai smallholders during the rainy season is 1.2l (Bekure *et al.* 1991, section 7.17). Given similar cattle size and lacking specialisation, it is assumed that milk offtake for cattle in ROMFARMS is also 1.2l. Redding (1981) assumed a yield of 0.33l of milk per day for adult sheep, however the size of sheep is larger in this study than in ROMFARMS. Adjusting for different sizes therefore, it is assumed that adult lactating sheep produce 0.2l of milk per day.

As only cattle are assumed to have been wintered inside, manure can only be collected in the period that cattle are kept inside. Manure from other animals remains where it falls in the field and is not accounted for in this study. The amount of manure produced by cattle is calculated as:

$$15) m_3 = \sum (tw_{cat}y),$$

where m_3 is the annual yield of manure from all cattle (kg), t is the period in days that manure can be collected, w_{cat} is the weight of cattle per age category ($_{cat}$) and y is the percentage of body weight produced daily as manure per animal.

The quantity of manure produced is assumed to be 6% of the animal's body weight per day (after Fokkens 1991; IJzereef 1981) and it is assumed that cattle are kept indoors for four months or 120 days.

Lastly, the annual yield of wool is calculated for sheep. Fleece is available only from immature or adult sheep. Wool is available only once per year from these animals and the yield is heavily dependent on the sheep breed. In ROMFARMS, it is assumed that the breed of sheep was an unimproved type such as the Soay sheep (after Wild 1970). The annual wool yield of an immature or adult sheep is therefore 2kg (after WildFibres 2008-2016).

ANIMAL	AGE CATEGORY	MEAT YIELD (KG)	MILK YIELD (L P.A)	MANURE YIELD (KG)	WOOL YIELD (KG)
SHEEP	Young	3	N/A	N/A	0
	Immature	5.625	N/A	N/A	2
	Adult	7.5	27	N/A	2
CATTLE	Young	21	N/A	252	N/A
	Immature	90	N/A	1080	N/A
	Adult	120	356	1440	N/A

Table 4.6. Annual meat yield (kg) per slaughtered young, immature and adult sheep or cow; annual milk yield (l) per lactating adult sheep or cow; annual manure yield (kg) per young, immature and adult cow. See appendix 3 for sources of assumptions.

4.3.6. Fuel and timber collection

Although the requirements of timber for the Roman army in the Dutch *limes* zone have been considered in some detail in previous research (see e.g. Kooistra *et al.* 2013; chapter 2 section 2.7) and to a lesser extent those of timber used by rural settlements, wood as a source of fuel is largely missing within discussions of the agricultural economy of the region. This is despite the importance that wood fuel has in pre-industrial societies. It was estimated by Malanima (2013, 17) that 50% of the energy consumption in the Roman world came from firewood. For rural regions, fuel would have been exclusively wood (see Veal & Thompson 2014). Although a recent

study (van Dinter *et al.* 2014) has included the demand and supply of fuel in the region, a discussion of fuel and timber collection has not been considered previously in a dynamic way and the labour costs associated with different strategies of collection are also missing.

Elsewhere, however, focus on fuel and timber collection has been considered in significant detail by archaeological, ethnographic and historical studies. Analysis of fuel and timber collection in archaeological studies used (according to Shackleton & Prins 1992, 632) mainly the Principle of Least Effort as an explanatory model for the types of charcoal assemblage that have been encountered at archaeological sites. However, Shackleton & Prins (1992) offer an alternative theoretical model framework whereby foragers will be selective when wood was prevalent whereas in landscapes with a scarcity of wood, foragers would collect wood indiscriminately. Shaw (2008, 69) argued, however, that there is no theoretical justification for assuming that proximity was the driving factor in fuel and timber collection. In addition, a list compiled by Brouwer *et al.* (1997) of cultural responses to wood scarcity reveal a range of strategies known from ethnographic sources of which indiscriminate collection strategies and reducing the distance travelled to collect wood were only two of many.

In ROMFARMS, settlements collect wood following the model proposed by Shaw (2008). Shaw advocated a combined patch choice and central place foraging model for fuel collection. A patch choice model concerns the length of time a forager should remain in an area where a resource is available. Shaw argued that in a patch choice model, foragers will remain in a patch where a resource is available until the net return from the patch falls below the mean net return of all patches (Charnov 1976; MacArthur & Pianka 1966). A central place foraging model recognises that foragers will often not consume resources where they are found in a landscape. Instead, foragers will bring foraged resources back to a site. Therefore, as the distance to resources increases, foragers should become more selective and target resources that will justify the increased time taken to reach the resource (see Orians & Pearson 1979 or Bettinger *et al.* 2015 for a detailed descriptions of central place foraging; see also Metcalfe & Barlow 1992; Bettinger *et al.* 1997). Variables noted by Brouwer *et al.* (1997) were incorporated, where possible, as mutable parameters to observe effects that different strategies by settlements would have had on labour expenditure in fuel and timber collection.

4.3.6.1. Fuel collection

In ROMFARMS, the values of four parameters affect settlements' behaviour in fuel collection: the quantity of wood available in the landscape, whether or not settlements maintain plots of coppiced woodland, the daily per capita fuel consumption of a settlement's inhabitants and the frequency that settlements need to collect fuel from the landscape (see figure 4.10; see also figure 4.11 for graphic representation of fuel collection process). The quantity of fuel required by settlements is calculated as:

$$16) w_1 = tnq,$$

where w_1 is the total quantity of fuel required (kg), n is the number of inhabitants in a settlement, q is the quantity of wood consumed per person per day and t is the length of one year in days.

After calculating the quantity of fuel required annually by settlements' inhabitants, settlements calculate the quantity of wood required to be collected each trip as:

$$17) w_2 = \frac{w_1}{\left(\frac{t}{F}\right)},$$

where w_2 is the quantity of fuel required per trip, w_1 is the total quantity of fuel required per year as calculated in equation 16, t is the length of one year in days and F is the frequency that settlements collect fuel.

The number of trips per year in which inhabitants will enter the landscape to forage for fuel depends on the value for the parameter “*collection-frequency*”. A value of 1 means that settlements will collect fuel every day, whereas a value of 50 means that settlements will collect fuel every 50 days and will therefore need to collect sufficient fuel to last 50 days.

For each settlement, the number of its inhabitants that need to forage for fuel in the landscape is then calculated. The main behavioural goal is to reduce the total number of its inhabitants needed to forage for fuel. Therefore, if the total amount of fuel that adult male inhabitants of a settlement can carry is more than or equal to the amount of fuel required to be collected each trip, the workforce is the minimum number of adult males needed to collect sufficient fuel. Otherwise, the workforce comprises all adult male inhabitants and the minimum number of adult female inhabitants required to collect the fuel that adult male inhabitants can not carry. If the amount that adult female inhabitants can collect is still less than the remaining required quantity of fuel, the workforce also includes the minimum number of adolescent or elderly inhabitants to collect any remaining fuel. If the workforce remains too small, settlements will not be able to collect sufficient fuel and the size of the deficit is recorded. The process is described below:

$$18) \text{ IF } w_2 \leq n_1\varphi_1 \text{ THEN } W = \frac{w_2}{\varphi_1},$$

$$\text{ELSE IF } (w_2 - n_1\varphi_1) \leq n_2\varphi_2 \text{ THEN } W = n_1 + \frac{w_2 - n_1\varphi_1}{\varphi_2},$$

$$\text{ELSE IF } (w_2 - (n_1\varphi_1 + n_2\varphi_2)) \leq n_3\varphi_3 \text{ THEN } W = n_1 + n_2 + \frac{w_2 - (n_1\varphi_1 + n_2\varphi_2)}{\varphi_3},$$

$$\text{ELSE } W = n_1 + n_2 + n_3, \delta = w_2 - \sum(n_{cat}\varphi_{cat}),$$

where w_2 is the quantity of fuel required per trip (kg) as calculated in equation 17, n_1 is the number of adult male inhabitants, φ_1 is the maximum load of an adult male, W is number of inhabitants required to collect fuel, n_2 is the number of adult female inhabitants, φ_2 is the maximum load of an adult female, n_3 is the number of adolescent or elderly inhabitants, φ_3 is the maximum load of an adolescent or elderly inhabitant. δ is the deficit of fuel (kg), n is the number of inhabitants per age and sex category ($_{cat}$) and φ is the maximum load of an inhabitant per age and sex category ($_{cat}$).

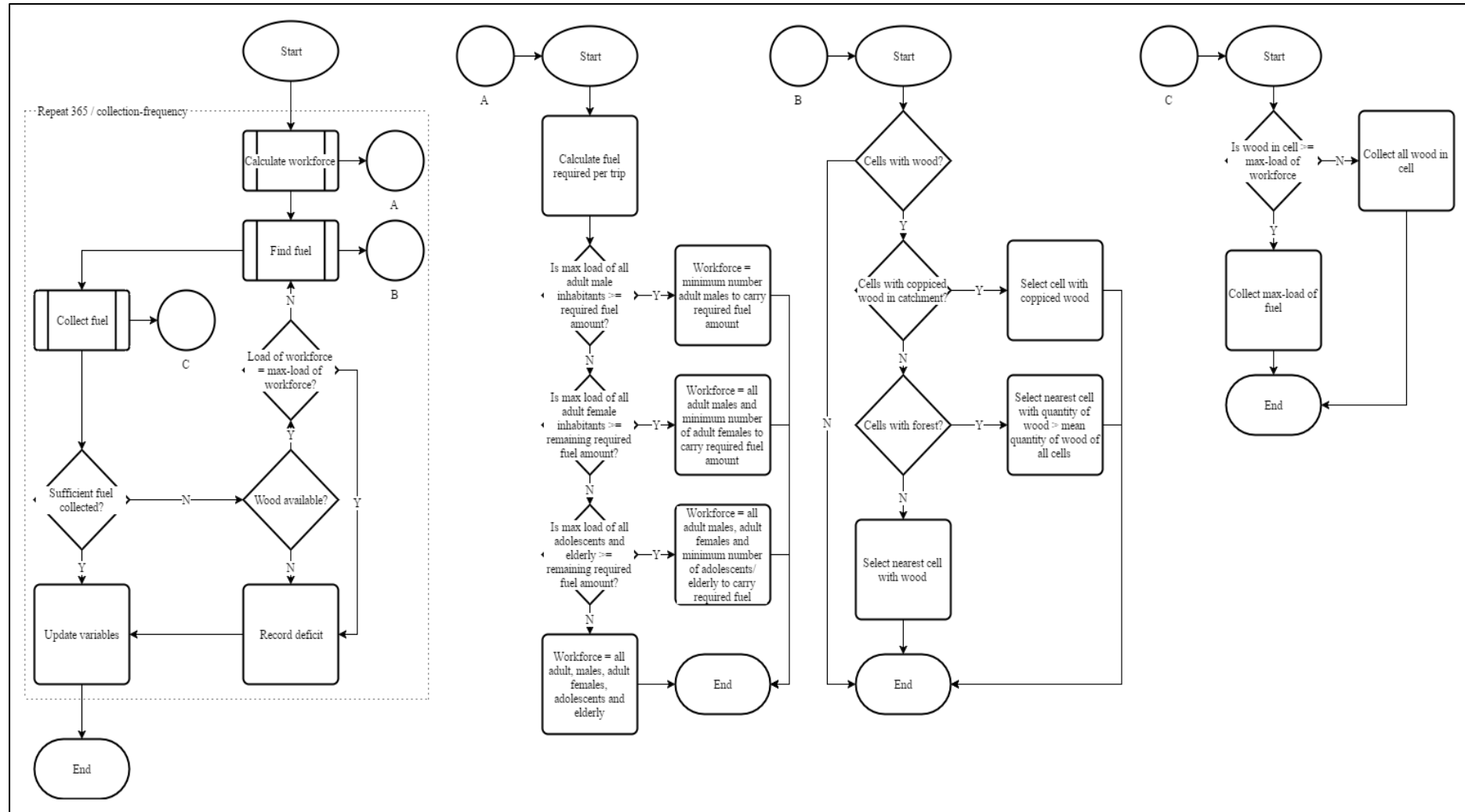


Figure 4.10. Flowchart of fuel collection sub-model that simulates foraging, processing and return of firewood to settlements.

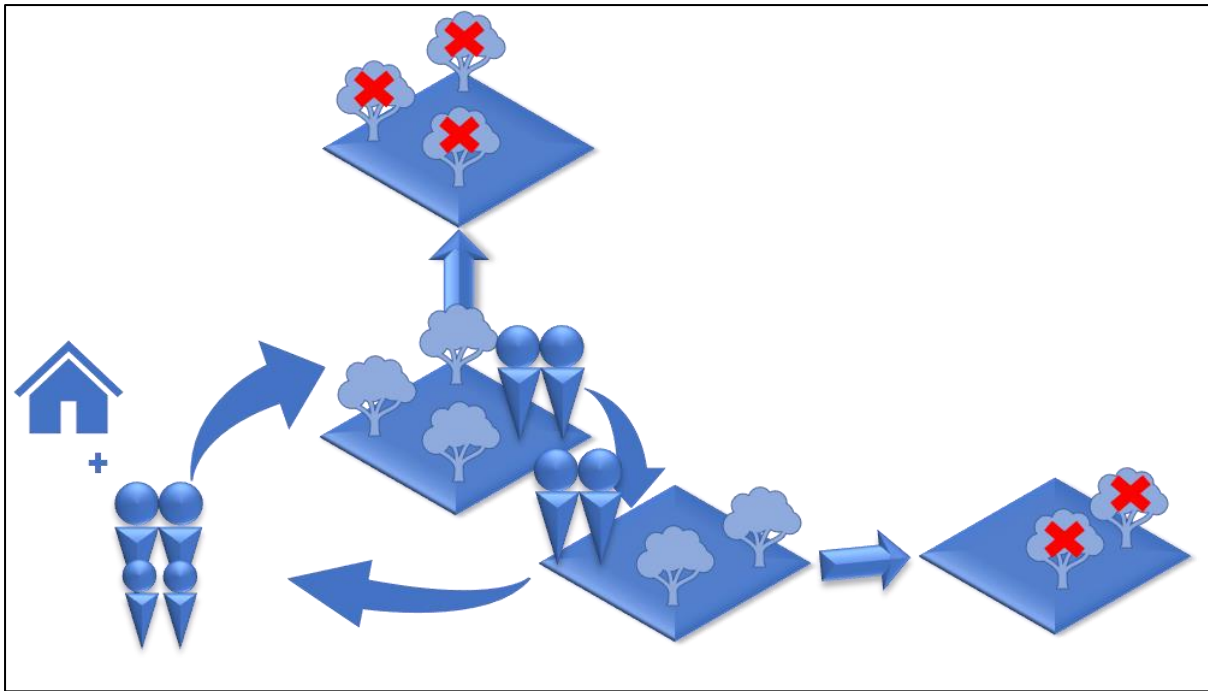


Figure 4.11. Graphic representation of fuel/timber collection showing how inhabitants of settlements move through the landscape depleting wood resources until they collect sufficient fuel/timber and return to the settlement

Foragers will subsequently search the landscape for a cell containing woodland. The primary behavioural goal of agents within the sub-model of fuel or timber collection is to collect sufficient fuel for the inhabitants of a settlement whilst minimising collection costs. Costs for fuel collection are the time taken for inhabitants of a settlement to travel to a cell containing wood, the time spent in a cell preparing wood for transport back to the settlement, and the time taken to return resources to a settlement. Settlements choose a cell to travel to collect fuel as follows (see figure 4.10). Settlements will first use a cell containing coppiced wood if any are within a settlement's catchment area and will continue using coppiced woodland until wood here is depleted. If no coppiced woodland is available, settlements will find the nearest cell containing more wood than the average of all cells containing woodland. Settlements will use any fen woodland present as a last resort for fuel only. Once an appropriate cell is located, the settlement will send the necessary number of its inhabitants to the cell to collect fuel or timber as calculated in equation 19. The inhabitants will remain in this cell until either sufficient wood has been collected, the cell is depleted of all wood, or the quantity of wood has fallen below the mean quantity of wood available in all cells. In the case of the latter two, the settlement will choose a new cell for inhabitants to forage in using the same weighted decision detailed above provided that the maximum load of the workforce has not been reached. If wood is still required but no cells remain with wood or the maximum load of the workforce has been reached, a deficit of fuel is recorded. At the end of the process, the workforce returns to the settlement with fuel.

The labour requirement in these sub-processes are the time taken to travel to collect fuel or timber and the time taking in each cell to process wood for fuel by each inhabitant sent to the cell. It is assumed that processing of wood for fuel within a patch takes three hours (after Brouwer

et al. 1997, 260, table 2).¹ Adult males can carry 30kg and adult women can carry 20kg (after Gregg 1988, 162). For children aged between 10 and 16, and the elderly can carry 15kg. A walking speed of 5km/hr is also assumed which falls between the upper and lower limits proposed by Pandolf *et al.* (1977). The total labour for fuel collection is calculated as:

$$19) l_1 = \sum (W_{d_i} \tau) + \sum W_{t_i}$$

where l_1 is the total labour expended by settlement's fuel-collecting workforce, W_d is the total distance travelled by each member of the workforce (i), τ is the walking speed (km/h) and W_t is the total time spent processing wood for fuel by each member of the workforce (i).

4.3.6.2. Timber collection

The process in which settlements collect timber from the landscape is similar to the process of fuel collection however differences are present (see figure 4.12). For the collection of construction wood, the quantity of timber required for the regular reconstruction of settlement buildings is immutable. Behaviour of settlements is determined by whether settlements maintain a plot of coppiced wood, the frequency of reconstruction and the quantity of woodland in the landscape. Visser (2008, 111; after Jeneson 2004, 24 cited in *ibid.*) assumed that the durability of Roman period byre houses in settlements was thirty years. Van Dinter *et al.* (2014, 48) assumed however a duration of ten years which corresponds to the estimated lifespan of alder wood which many settlement buildings were constructed from in the Dutch *limes* zone (see Meier 2008-2015). Owing to disagreement regarding the frequency of reconstruction, this is a mutable parameter in ROMFARMS. The quantity of timber required for the reconstruction of settlement buildings is different depending on the number of households of the settlement. Van Dinter *et al.* (2014, 44 after Bult & Hallewas 1987; van der Velde 2008) assumed that the main buildings of a farmstead in the Early Roman period had a surface area of 82m² and 103m² with 0.21m³ of wood used per m². In ROMFARMS an average of the two is used and the buildings for each household had a surface area of 92.5m². Accordingly, each household required 19.42m³ of timber. It is assumed that the majority of wood used for construction was locally available alder timber which has an average dry mass of 439kg/m³ (Zanne *et al.* 2009). Therefore, a settlement with one household requires 8525.4kg of timber. It is further assumed that this requirement is for both byre houses and associated buildings such as palisades, granaries and outhouses with half of the requirement for the construction of houses and half for other buildings (Visser 2008, 110-111).

The quantity of timber required is calculated as:

$$20) w_3 = nw,$$

where w_3 is the total amount of timber required, n is the number of households a settlement possesses, and w is the quantity of timber required per household (kg).

The frequency in which inhabitants will enter the landscape to forage for timber depends on the value for the parameter "*reconstruction-frequency*". A value of 1 means that settlements must collect timber every year, whereas a value of 50 means that settlements will collect timber every 50 years. When settlements are required to collect timber, only adult male and female inhabitants can collect timber. Unlike fuel collection, if a settlement can not collect sufficient timber in a single trip, subsequent trips can occur. The process of timber collection repeats until all wood is depleted in the landscape or sufficient timber has been collected. It is extremely likely that timber collection and the reconstruction of settlement buildings relied on communal labour in the past.

¹ Brouwer *et al.* (1997, 260 table 2) provide responses to a survey taken from four villages in Malawi. The median collection for fuel by these villages was twice weekly, with a median time of six hours spent. Therefore, it is assumed that each trip took three hours.

As ROMFARMS does not consider the role of communal labour, the workforce for timber collection per settlement is calculated as:

$$21) \text{ IF } w_3 \leq n_1 \varphi_1 \text{ THEN } W = \frac{w_3}{\varphi_1},$$

$$\text{ELSE IF } (w_3 - n_1 \varphi_1) \leq n_2 \varphi_2 \text{ THEN } W = n_1 + \frac{w_3 - n_1 \varphi_1}{\varphi_2},$$

$$\text{ELSE } W = n_1 + n_2,$$

where w_3 is the quantity of fuel required per trip (kg) as calculated in equation 20, n_1 is the number of adult male inhabitants, φ_1 is the maximum load of an adult male, W is the number of inhabitants required to collect timber, n_2 is the number of adult female inhabitants, φ_2 is the maximum load of an adult female.

The selection of a cell to collect timber is the same as for fuel collection (see figure 4.10).

The total labour for timber collection is calculated as:

$$22) l_2 = \sum (W_{d_i} \tau) + \sum W_{t_i},$$

where l_2 is the total labour expended by settlement's timber-collecting workforce, W_d is the total distance travelled by each member of the workforce (i), τ is the walking speed (km/h) and W_t is the total time spent on processing wood for timber by each member of the workforce (i).

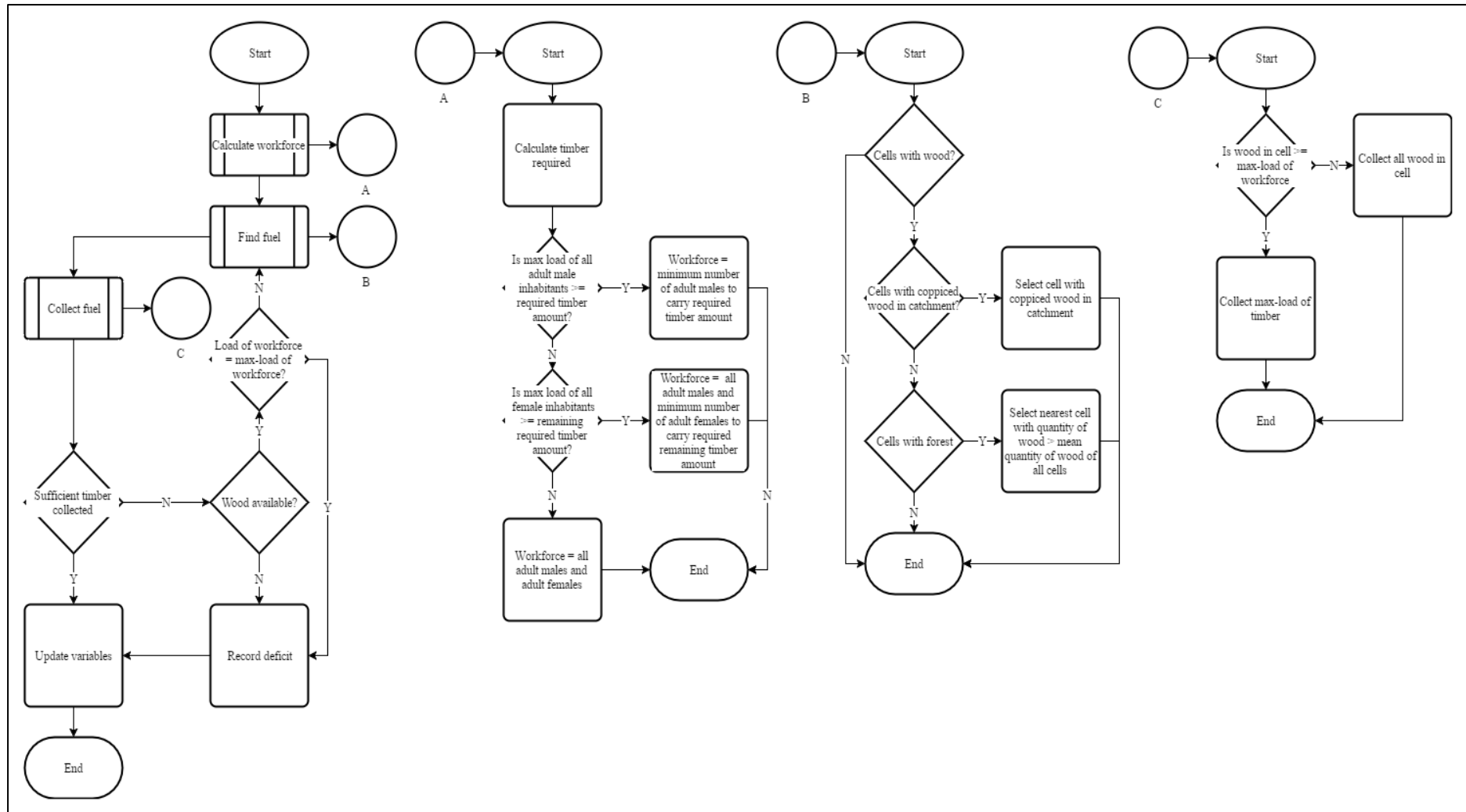


Figure 4.12. Flowchart of timber collection sub-model that simulates the foraging of wood for construction in the landscape.

4.4. Description of experiments

As discussed above (section 4.2), ROMFARMS is scenario-based in which experiments with different parameter values are combined to reflect different complete agricultural strategies. The parameter values for the various scenarios simulated as part of this research are given in table 4.7. Initial experiments were conducted to gain a better understanding of the limits for each of the four agricultural tasks in a subsistence-based agricultural economy. In addition, by exploring the parameter space of ROMFARMS, the results were analysed to produce optimum agricultural strategies for settlements practicing subsistence-based agriculture. Subsequently, different scenarios of surplus production were simulated to assess the land and labour costs of each strategy. Accordingly, the limits of each strategy could be gauged. Furthermore, the results were analysed to improve understanding of feasible ways that settlements could produce a surplus for military and civilian settlements in the Dutch *limes* zone. Using palaeogeographic data, experiments could also be conducted using the same scenarios but in reconstructed landscapes.

Scenarios were simulated using NetLogo's in-built BehaviorSpace function. BehaviorSpace allows for a model to be run many times, automatically recording outputs and iterating over different parameter values also known as "parameter sweeping". BehaviorSpace enables an efficient exploration of a sample of the parameter space or the set of all possible parameter values. This allows for the identification of which combinations produce which behaviours.

A description of the various scenarios simulated for this study are given below:

A) Subsistence-based agriculture

- I. Subsistence-based arable farming: settlements undertake neither extensive or intensive arable farming and practice biennial fallow. Values for parameters "*store-size*" and "*%-calories-from-crops*" were explored to analyse land and labour costs for different subsistence-based arable farming strategies.
- II. Subsistence-based animal husbandry: Values for parameters "*sheep-strategy*" and "*cattle-strategy*" were explored to simulate settlements exploiting sheep and cattle for:
 - a. meat, or
 - b. milk, or
 - c. secondary products (wool from sheep, manure from cattle)

The land and labour costs for different animal husbandry practices were evaluated. In addition, the yields of animal products were calculated and compared with yields from arable farming to observe basic requirements for consumption from food production activities by settlements undertaking subsistence-based agriculture.
- III. Fuel collection: Values for parameters "*collection-frequency*", "*daily-per-capita-fuel-use*", "*forest-cover*" and "*fen-cover*" were explored to observe the effects on labour costs that different collection strategies and different quantities of wood available in the landscape. Possible deficits were compared with labour costs to identify optimal fuel collection strategies.

B) Surplus agricultural production

- I. Surplus arable production: values for parameters "*arable-strategy*" were explored to analyse land and labour costs for intensive and extensive arable strategies. The estimated quantity of surpluses was also recorded in order to compare cost-efficiency of the two simulated surplus arable strategies.
- II. Surplus animal husbandry: animal husbandry strategies exploiting herds and sheep for different products were simulated via the parameters "*no-herds*",

“*cattle-strategy*” and “*sheep-strategy*” to identify extent of surplus animal products and the associated land and labour costs. Manure production by cattle herds was also recorded to observe the limitations on intensive arable farming. In addition, land and labour costs for horse herds were analysed as well as the possible number of surplus horses available each year.

C) Agriculture in reconstructed landscapes

- I. Arable farming was simulated diachronically in micro-regions using settlement densities from the Late Iron Age to the Middle Roman period to:
 - a. Analyse available surpluses of cereals in each sub-region and compare with demands from non-native settlements such as forts and *vici*.
 - b. Observe the limitations of the availability of different land types on agricultural tasks
 - c. Generate new hypotheses regarding possible supply mechanisms from rural settlements to *castella*, *castra*, *vici* and towns
- II. Labour and land costs for simulated livestock herds were compared with supply in micro-regions to:
 - a. Analyse the possible maximum extent of surplus animal husbandry in each micro-region
 - b. Identify possible indications where competition for resources may have occurred in micro-regions among different elements of the agricultural economy

SCENARIO	PARAMETER	VALUE(S)	INCREMENT	NOTES
A	no-1-household-settlements	0/2	-	
	no-2-household-settlements	0/2	-	
	no-3-household-settlements	0/2	-	
	no-5-households-settlements	0/2	-	
	runtime	100	-	
	region	"hyp"	-	
	period	N/A	-	
	area-levee	0.5	-	
	area-floodbasin	0.5	-	
	forest-cover	0.1	-	
	fen-cover	0	0	
	%-calories-from-crops	0.1-1.0	0.1	
	store-size	1.0-2.0	0.25	
	strategy-arable	"none"	-	
	surplus-takeoff	0	-	
	daily-per-capita-fuel-use	1.0-10.0	1.0	
	coppicing?	N	-	
	collection-frequency	1.0-7.0	1.0	
	reconstruction-frequency	10.0-30.0	10.0	
	cattle?	Y/N	-	
	sheep?	Y/N	-	
	horse?	N	-	
	sheep-strategy	"meat", "milk", "wool"	-	
	cattle-strategy	"meat", "milk", "manure/traction"	-	
B	no-1-household-settlements	0/2	-	
	no-2-household-settlements	0/2	-	
	no-3-household-settlements	0/2	-	
	no-5-households-settlements	0/2	-	
	runtime	100	-	
	region	"hyp"	-	
	period	N/A	-	
	area-levee	0.5	-	

	<i>area-floodbasin</i>	0.5	-	
	<i>forest-cover</i>	0.1	-	
	<i>fen-cover</i>	0	-	
	<i>%-calories-from-crops</i>	0.1-1.0	0.1	
	<i>store-size</i>	1.5	-	
	<i>strategy-arable</i>	"extensification" /"intensification"	-	
	<i>surplus-takeoff</i>	0.1-1	0.1	for "extensification" (for "intensification" surplus take-off = 1.0)
	<i>daily-per-capita-fuel-use</i>	6	-	
	<i>coppicing?</i>	Y	-	
	<i>collection-frequency</i>	1	-	
	<i>reconstruction-frequency</i>	20	-	
	<i>cattle?</i>	Y/N	-	
	<i>sheep?</i>	Y/N	-	
	<i>horse?</i>	Y/N	-	
	<i>sheep-strategy</i>	"meat", "milk", "wool"	-	
	<i>cattle-strategy</i>	"meat", "milk", "manure/traction"	-	
C	<i>region</i>	1-32		
	<i>period</i>	"IJZ", "ROMVA", ROMVB", "ROMMA", A", "ROMMB"		
				NB. Other values same as scenarios A & scenarios B

Table 4.7. Parameter values for scenarios simulated in ROMFARMS.

5. Subsistence-based farming

In the previous chapter, an overview of the various scenarios to be simulated were given (see chapter 4 section 4.4). In this chapter, the results from experiments undertaken to simulate the subsistence-based agricultural economy of the Dutch *limes* zone in a randomly-generated landscape will be discussed (experiments A I-III) in light of objectives i-iv (see chapter 3 section 3.3). The same experiments were simulated also in reconstructed landscapes and discussed in chapter 6. By undertaking an analysis of the pre-Roman agricultural economy, comparisons regarding surplus and subsistence agricultural strategies can be made. In particular, this chapter concerns the following research topics:

- a) Population dynamics of total populations within a landscape and internal population dynamics within settlements
- b) Supply and demand from settlements under subsistence-farming:
 - a. The quantities of grain and animal products produced and required under a subsistence-based economy,
 - b. The requirements of land and labour of arable farming, animal husbandry and fuel and timber collection,
 - c. The supply of labour from the inhabitants of settlements
- c) The relative importance of limiting factors in a subsistence-based mixed agricultural economy.

5.1. Population dynamics

The demand and ability to produce or collect food and fuel derive solely from the supply and demand from the inhabitants of settlements in ROMFARMS. Thus, the analysis of internal population dynamics as well as an analysis of the dynamics of the whole population in a randomly generated landscape is essential to understand how changes in demand and the supply of labour affected agricultural behaviour in the model in a dynamic way. It must be noted however that simulations in ROMFARMS produce only highly idealised populations that emerge from assumptions drawn from data that must be used cautiously. The settlement populations are not supposed to be realistic although they emerge from the best available data.

Population growth in each year is provided in figure 5.1 for scenarios with different numbers of households. Population growth in all scenarios fluctuates initially but stabilises somewhat after fifty years. To reduce the total number of simulated scenarios, the scenarios in ROMFARMS have used only stable populations rather than different population profiles such as growth and decline that have been used in other research (Danielisová & Štekerová 2015). Accordingly, results from simulations were analysed only after year 50 when populations stabilise. Population growth after populations have stabilised is modest regardless of the number of households each settlement has. Mean population growth per year after year 50 falls between 0.94 and 1.08%. This corresponds to the population growth cited by Verhagen *et al.* (2016a) in scenarios using Model West Level 3 Female life table (Coale & Demeny, 1966; Hin 2013) and the South High Mortality with $e_0=25$ life table (Woods 2007; Hin 2013) but lower than the growth rate assumed by Danielisová *et al.* (2015). In scenarios with larger settlements, the fluctuations in population growth from one year to the next are smaller after the fiftieth year. The fluctuations grow larger as the number of households decrease. In scenarios with larger settlements, the population size and, in particular, the marriage pool is larger. This means that populations are less likely to become extinct before 100 years as adults have a greater probability of finding spouses and continuing their reproductive potential for longer. Population sizes in scenarios with

smaller settlements are more stochastic with more simulations ending before 100 years. The range of results is therefore larger.

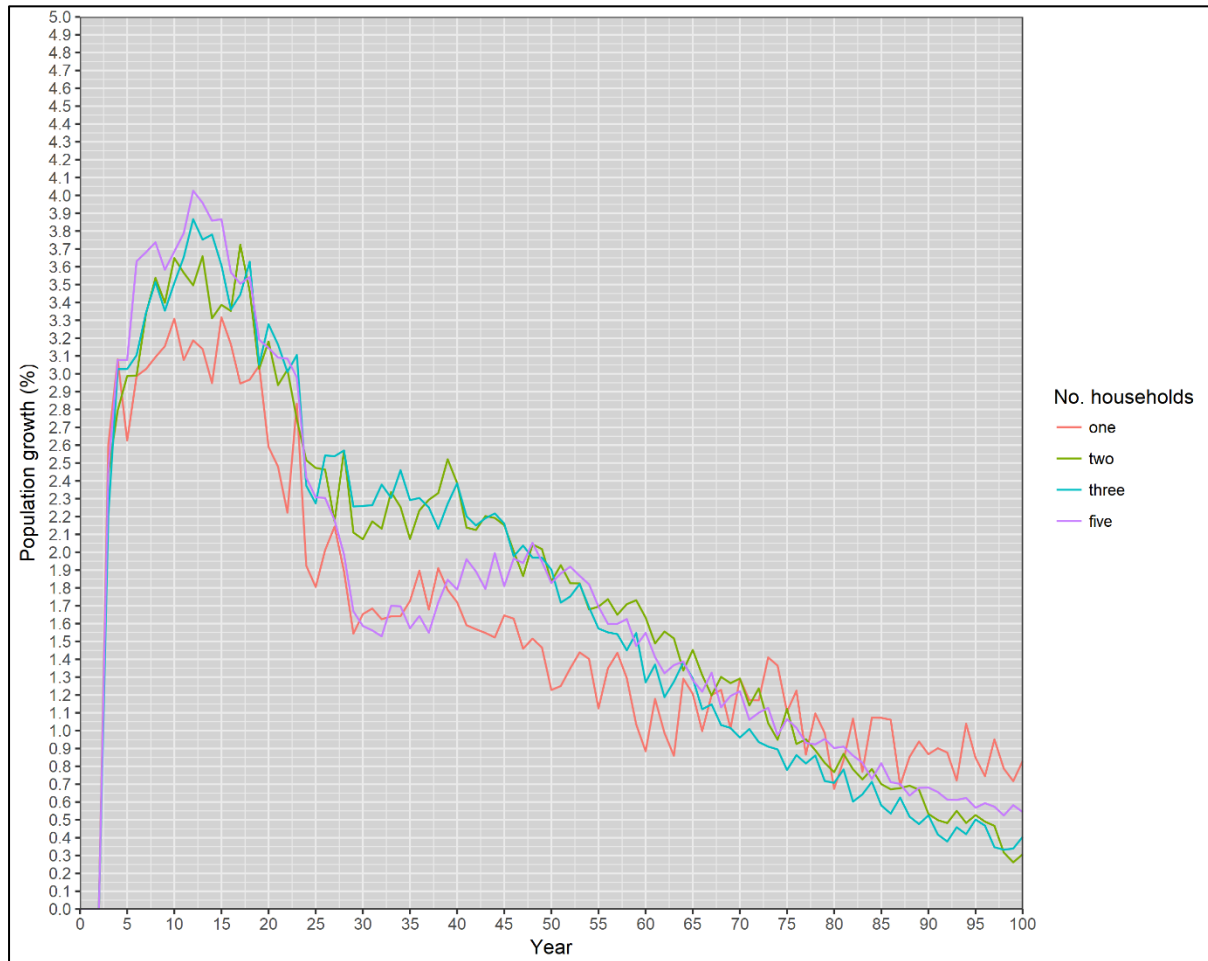


Figure 5.1. Population growth (%) per year in scenarios with settlements with different number of households (all years).

The proportion of inhabitants per age category in settlements with different numbers of households is given in figure 5.2. In all settlements, the number of adults and children are approximately equal with only very few elderly individuals. The higher mortality rates assumed for elderly individuals results in only few surviving each year. In settlements with more than one household, the number of children (individuals aged 0–15) is in excess of adults (individuals aged 16–49) and vice versa in settlements with one household. Although population growth stabilises on average, there remains a large range in the total number of inhabitants in each settlement. This is owing to stochasticity in both the mortality and reproduction processes within the population dynamic sub-model.

As the size of the settlement increases, the mean number of children per adult women also increases. The number of children born to each woman in scenarios with settlements possessing five households (12.23) is slightly in excess of those born to each woman in settlements with one household for example (10.94). In scenarios with larger settlements, the larger population size increases the marriage pool increasing the probability that a woman remains married and capable of reproducing. The mean number of children born to each adult woman is higher in the results from ROMFARMS than estimated previously. Between five and seven children per woman has often been assumed in pre-industrial societies (see Wrigley & Schofield 1981; Campbell & Wood 1988; Bentley *et al.* 1993; Bocquet-Appel 2008). Specifically,

for the Roman Empire, Frier (1982) argued that 5.84 children per woman was necessary to keep the population stationary if Ulpian's Life Table was indicative of mortality. Parkin (1992) claims at least 5.1 children per woman was necessary when using Model West Level 3 life table which is used in ROMFARMS. Scheidel (2007) assumes six to nine children per woman was necessary to maintain population levels. In ROMFARMS there are fewer restrictions on reproduction than was likely in the past. Verhagen *et al.* (2016a) apply a marital age of at least 25 for adult men and 18 for adult women which has an impact on the length of time adults can continue reproducing. In addition, the mean number of children per woman cited in previous research are the assumed number necessary to keep a population stationary. In ROMFARMS modest population growth emerges from the sub-model of household population dynamics.

NO. HOUSEHOLDS	"STRONG" WORKFORCE	"WEAK" WORKFORCE
ONE	2.09	3.24
TWO	2.71	4.32
THREE	3.65	5.92
FIVE	5.64	9.14

Table 5.1. Average size of "strong" and "weak" workforces available to settlements with different sizes.

By analysing the household population dynamics within settlements, the supply of labour from settlements of different sizes can be gauged. As discussed in section 4.3.3 of chapter 4, the workforce available to a settlement is comprised solely of inhabitants of the settlement. Workforces are separated between the "strong" (all adults) and the "weak" workforce (children aged 10 to 15 and the elderly). The mean size of the "weak" and "strong" workforces inhabiting each settlement are provided in table 5.1. Settlements with more households, by virtue of their larger populations, have larger workforces available to them. However, households in settlements with more than one household are generally incomplete. Incomplete households are those with fewer than the maximum number of married adults as one household in ROMFARMS comprises one married couple and any dependents. For example, a settlement with two households would be expected to contain at least two married adult males and two married adult females, and a settlement with five households would be expected to contain five adult males and five adult females. The impact of incomplete households has been considered previously by van Dinter *et al.* (2014) as a possible limiting factor of agricultural productivity in the region. The impact of incomplete households is particularly pertinent to agricultural productivity in the Roman period when considering the significant recruitment of the local male population (see chapter 2 section 2.3).

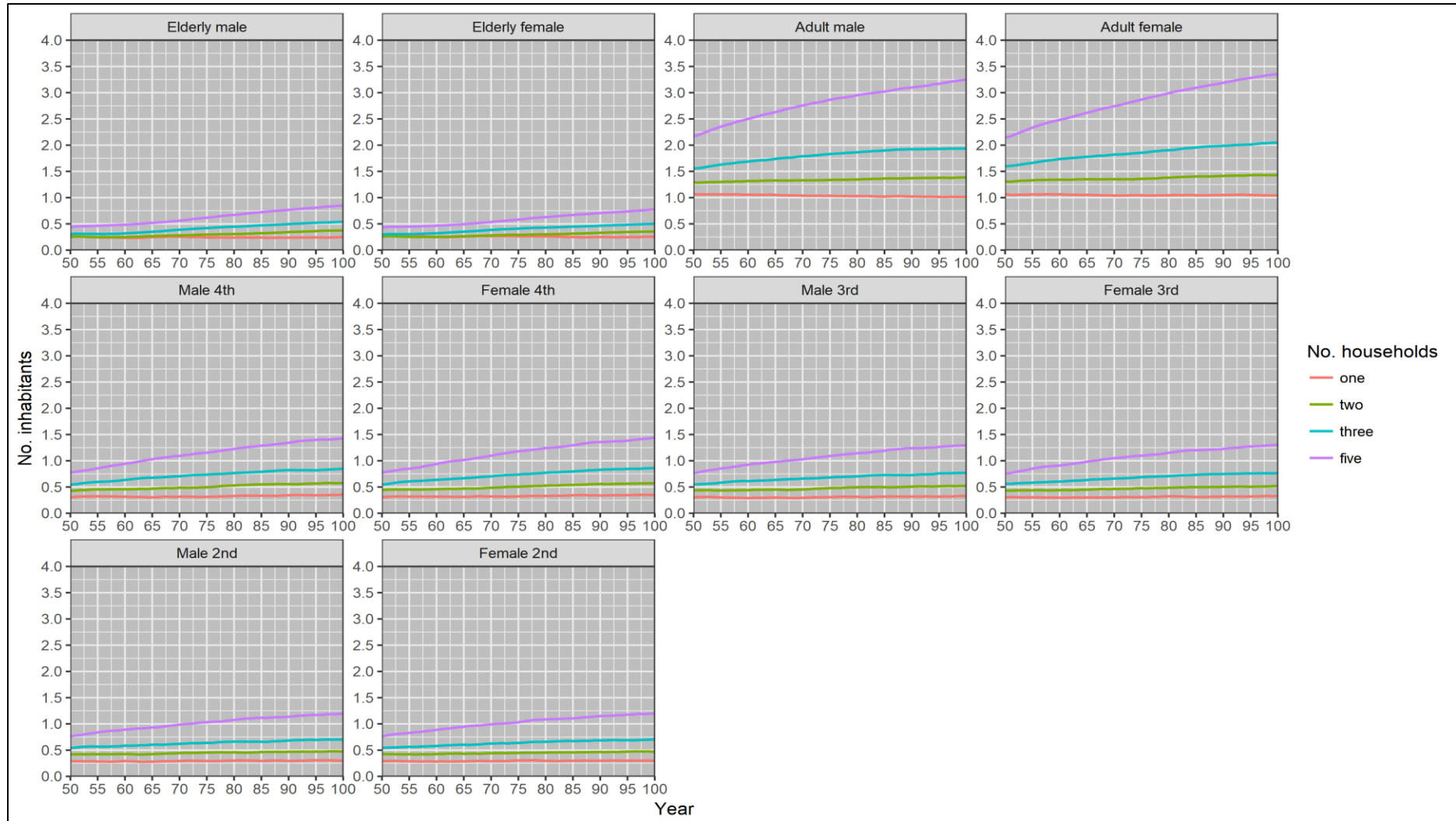


Figure 5.2. Total number of inhabitants per age category in settlements of different sizes. NB ROMFARMS records the number of inhabitants at the end of each year therefore the number of inhabitants aged 0 to 1 category is recorded as zero each year.

5.2. Arable farming

In the Late Iron Age in the Lower Rhine delta, native farmers undertook a subsistence-based arable strategy. Surpluses were not produced except, perhaps, a small surplus that would have served as a buffer and for use in social exchange (see chapter 4 section 4.3.4). By simulating the subsistence economy assumed for the pre-Roman Late Iron Age, the demand for arable land and labour for arable tasks by settlements with dynamic populations can be estimated (objective ii, see chapter 3 section 3.3). Comparing these demands with the available land and labour, the relative importance of limiting factors within arable farming can be gauged (objective iii). In addition, the total grain produced each year by settlements of different sizes can be compared with the grain required for consumption by settlements to assess when too little or more than enough grain is cultivated (objective iv).

5.2.1. Principal determinants

The area of arable land required by settlements is determined primarily by the quantity of grain needed for consumption by settlements. This is determined by the number of inhabitants within a settlement and the annual calorific demands of each inhabitant. Grain is not however the sole foodstuff for inhabitants and the quantity of grain required is adjusted by the proportion of food derived from other sources such as animal products. Settlements dependent on grain to supply 70% of the total calories required by inhabitants will need to produce more grain than settlements deriving 60% of the required calories from grain. In addition, the area of land required is further adjusted by the size of the buffer that settlements cultivate. Settlements cultivating a buffer of 1.5 need to increase the area of land cultivated to produce an extra 50% of grain. Lastly, settlements must also cultivate sowing seed for use in the following year. Given that settlements are unable to predict the quantity of grain required for the following step, the area of land required for the production of sowing seed is based on the required grain by the settlement's inhabitants in the current year. This has an impact on whether agents can cultivate sufficient land, therefore. For example, a household population that expands significantly in the following year will need more sowing seed than predicted in the previous year which the agent may not possess.

The area of arable land cultivated each year is therefore determined by the quantity of grain needed by a settlement for consumption, sowing seed and a possible buffer. The minimum area of land that must be cultivated by settlements to produce sufficient grain is provided in figure 5.3. These results show that the minimum area of arable land required to be cultivated by settlements increases as the number of households increase and as the proportion of calories derived from grain increase.

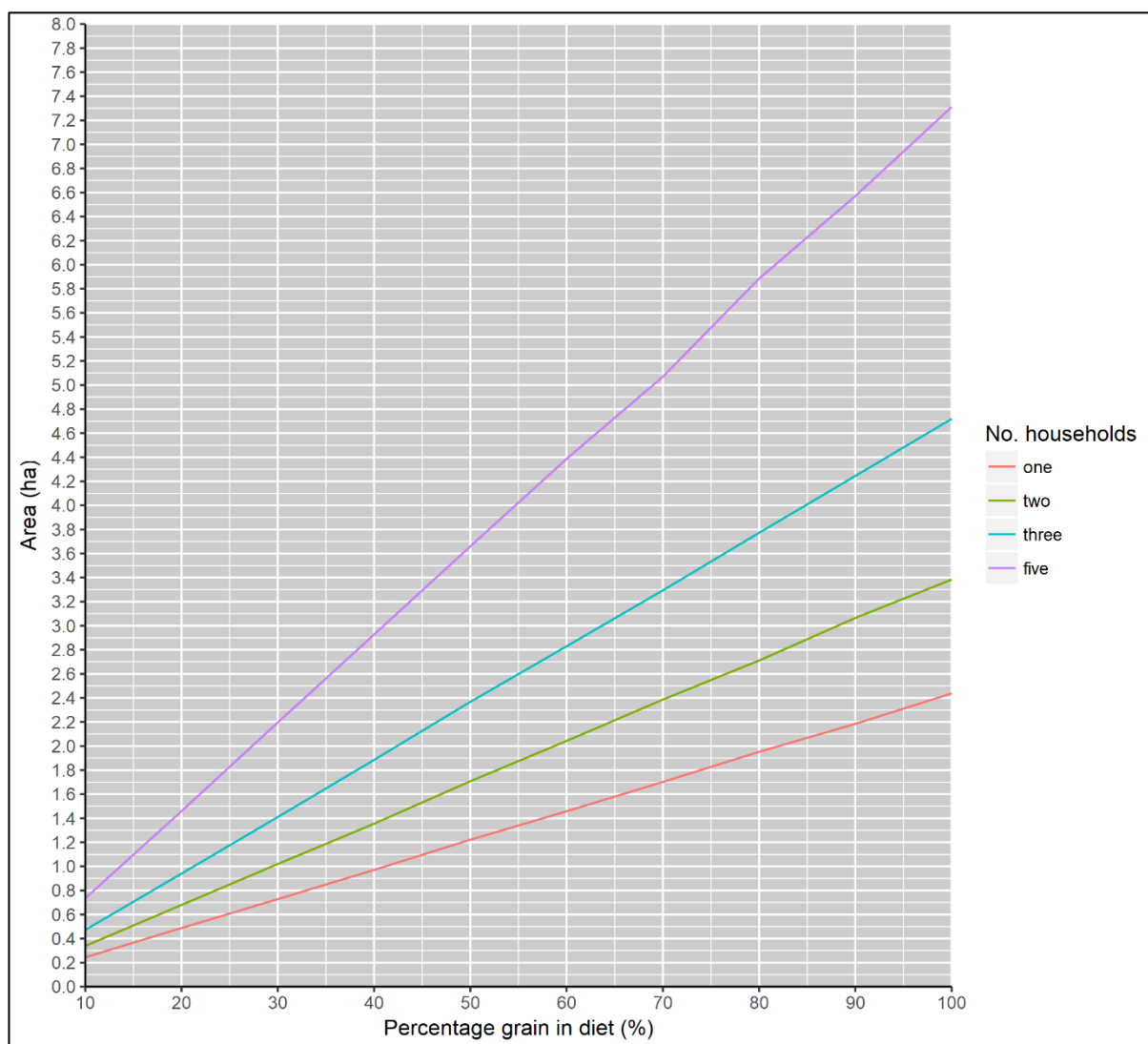


Figure 5.3. Minimum area of land required to be cultivated by settlements with different number of households to produce grain for consumption, sowing seed and a buffer of 50% in scenarios with different proportions of grain-derived calories (year ≥ 50).

5.2.2. The importance of buffers

The production of a small surplus of food each year by settlements undertaking subsistence-based agriculture has often been cited as characteristic of the behaviour of risk-averse farmers (see chapter 4 section 4.3.4). Experimenting with scenarios in which settlements cultivate differently sized buffers has indicated the impact that this behaviour has on the ability of settlements to produce sufficient grain. The minimum area of land required to be cultivated according to different buffer sizes is provided in figure 5.4 and compared with the actual area of land cultivated by settlements each year. When settlements cultivate a buffer of less than 40% corresponding to a value of 1.4 for the parameter **store-size**, settlements are unable to cultivate the minimum area of land necessary.

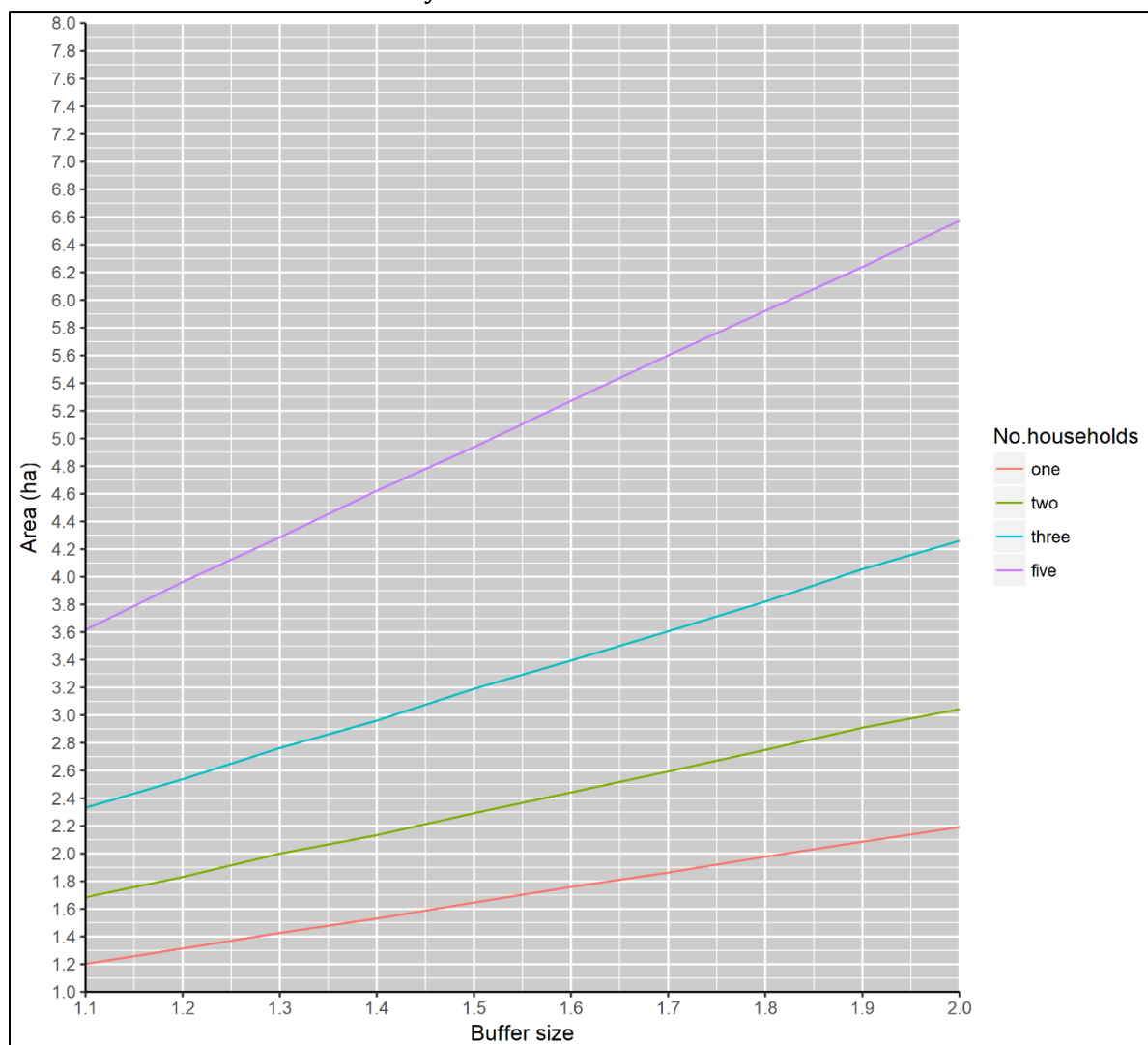


Figure 5.4. Minimum area of land required to be cultivated by settlements with different number of households to produce grain for consumption and sowing seed where 67.5% of the total required calories are derived from grain in scenarios with different sized buffers (year ≥ 50).

Although larger buffers provide more protection and allow for greater population expansion, their production would more resemble surplus production as opposed to risk-averse subsistence farming. Furthermore, larger buffers place greater demands on the principal limiting factors: sowing seed, land and labour. Comparisons between the minimum area of land necessary to be cultivated by settlements and the actual area of land cultivated (cf. figures 5.3 & 5.4) indicate

that a buffer of 40% is sufficient to ensure settlements can cultivate sufficient land, however this can still result in small deficits. Grain deficits encountered by settlements cultivating differently sized buffers are provided in figure 5.5. A buffer of at least 50% results in smaller deficits than occur when settlements cultivate a buffer of 40%. Still larger buffers do not reduce deficits further. The cultivation of larger buffers would therefore not be necessary, given the extra land and labour costs, for risk-averse settlements practicing subsistence farming.

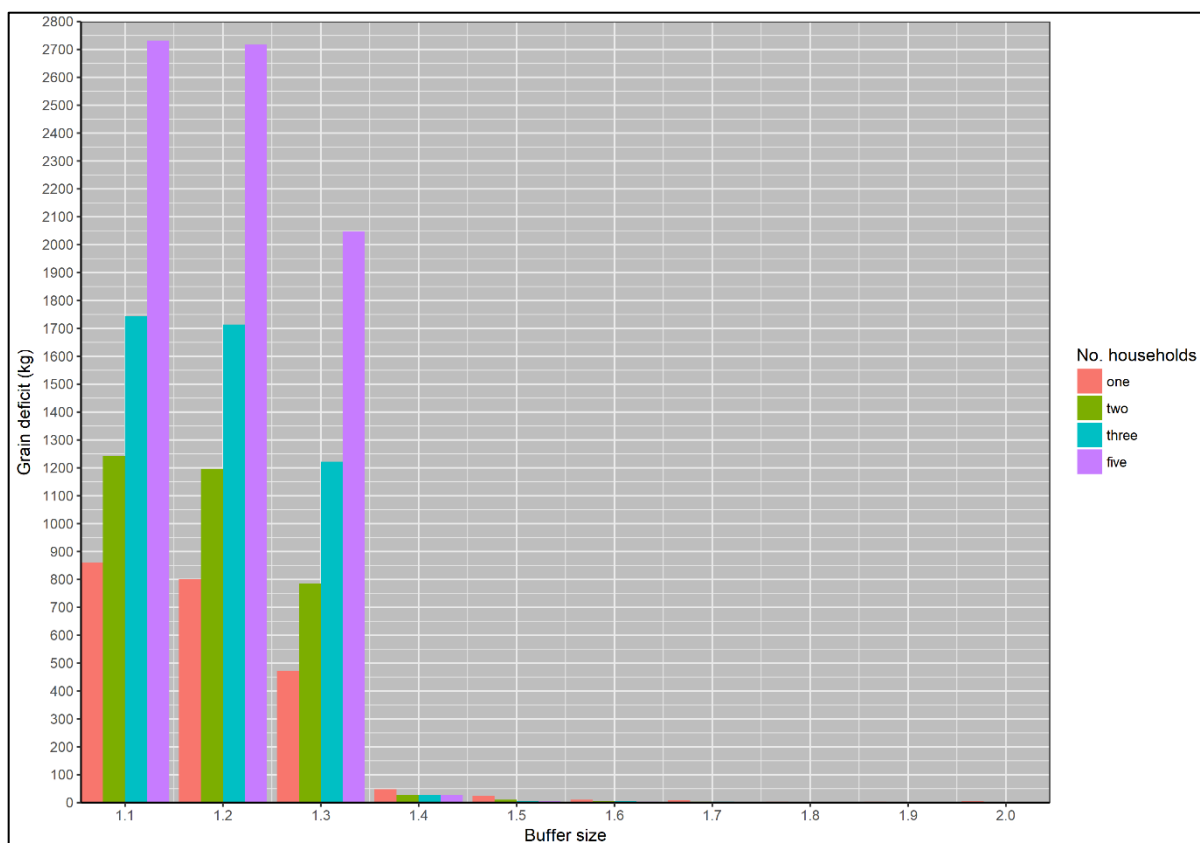


Figure 5.5. Grain deficits per settlement with different number of households in scenarios with different sized buffers (year ≥ 50).

The production of a buffer in ROMFARMS protects settlements against negative fluctuations in grain yield and allows for changes in population size. Increases in the demand for grain from a settlement's inhabitants can not be predicted by settlements in the previous year. The increased area of land to be cultivated and the sowing-seed required can not be predicted either. By cultivating a buffer, an increase in the required sowing seed can be met by this small surplus. Without a buffer of at least 50% extra grain, a positive feedback loop occurs in which decreases in the availability of sowing seed results in decreases in the area of land cultivated (see figure 5.6). This in turn causes a decrease in grain produced and therefore decreased sowing seed for the following year.

5.2.3. Limiting factors

For arable farming, the availability of land, labour and sowing seed have been identified as the principal factors limiting arable farming. Without sufficient land, labour and sowing seed, settlements are unable to cultivate sufficient land to produce enough grain for consumption, sowing seed for the following year and the necessary buffer of 50%.

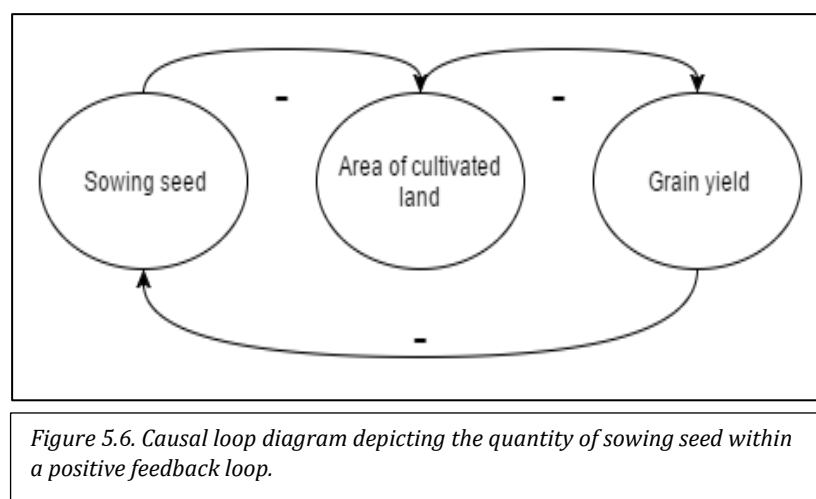


Figure 5.6. Causal loop diagram depicting the quantity of sowing seed within a positive feedback loop.

5.2.3.1. Availability of land

To successfully produce sufficient grain for consumption, a buffer and sowing seed for the following year, settlements must have access to sufficient land. The minimum area of land required by settlements to produce sufficient grain has already been provided in figure 12. Settlements will, however, require access to a greater area of land if fallowing is undertaken. Under subsistence-based arable farming, settlements undertake biennial fallow whereby arable land used in one year can not be cultivated in the following year. Settlements practicing subsistence-based arable farming therefore need each year twice the area of land that is needed to be cultivated: the area to be cultivated and the same area to be left fallow.

In randomly-generated landscapes, the availability of arable land is not expected to be a limiting factor as the total area available is not realistic. In chapter 7, farming in reconstructed landscapes is discussed wherein the area of arable land is more realistic. Accordingly, the relative limiting impact that the availability of land has on subsistence-based arable farming can not be gauged from the results of these initial experiments. Nevertheless, the area of arable land available to settlements each year remains substantially higher than the area of land that can be cultivated by the settlements' workforces or the area that can be sown by the available sowing seed to settlements. Less land is available on average each year in scenarios where the inhabitants of settlements rely on grain for a greater proportion of the calories they need or when settlements comprise more households. In these scenarios, there is increased competition for arable land between settlements, however the area of arable land available does not become limiting or restrict settlements in cultivating the necessary area of land to produce enough grain.

5.2.3.2. Availability of labour

The labour pool for tasks within subsistence-based arable farming (ploughing, sowing, harvesting) is limited given that only adult males and females can undertake them. The size of the labour pool would thus have a limiting factor on the ability of agents to cultivate sufficient arable land. Of the three tasks of subsistence-based arable farming, ploughing and harvesting together account for the vast majority of labour expended. Between 95% and 98% of the total number of hours spent by a settlement in arable is in ploughing and harvesting owing to the in-built assumptions in ROMFARMS. The total hours expended by settlements are provided in table 5.2.

Comparing the maximum area of land that can be cultivated by the “strong workforce” available to settlements with the minimum area of land that settlements must cultivate indicates however that the available labour to settlements would not restrict settlements’ ability to cultivate sufficient land. The total area of land that can be cultivated by settlements with the available workforce is provided in table 5.3 (cf. the minimum area of land to be cultivated in figures 5.3 & 5.4). The area of land that can be cultivated is consistently higher than the minimum area necessary to produce sufficient grain for settlements. Thus, although arable tasks rely on a limited labour pool, the availability of labour under a subsistence economy does not restrict the ability of agents to produce enough grain under average demographic conditions.

NO. HOUSEHOLDS	SUBSISTENCE	INTENSIFICATION	EXTENSIFICATION
ONE	96.77	150.30	335.01
TWO	136.10	207.82	475.04
THREE	187.40	286.99	671.20
FIVE	289.09	444.56	1062.42

Table 5.2. Total hours expended within arable farming by settlements undertaking subsistence-based arable farming, intensification or extensification with different number of households to produce grain for consumption and sowing seed where 70% of diet is grain based and settlements cultivated 50% extra each year as a buffer (year ≥ 50).

5.2.3.3. Availability of sowing seed

Without sufficient sowing seed, settlements are unable to cultivate enough arable land even if they have access to both sufficient land and labour. As discussed above, the availability of sowing seed is part of a positive feedback loop in which shortage of sowing seed in one year has a cumulative effect on the ability of agents to produce sufficient grain in subsequent years. If settlements produce insufficient sowing seed for the following year, they will be unable to sow sufficient land in the following year. In the following year, even less sowing seed will be available for the year after that.

Provided that a buffer of 50% is cultivated, settlements will possess sufficient grain to cultivate the minimum area of land necessary to produce enough grain for food for the inhabitants, sowing seed and the necessary buffer. Comparisons between the area that can be sown with sowing seed available to settlements in table 5.3 and the area needed in figure 5.3 shows that the former area is larger than the latter. However, the area of land that can be cultivated with sowing seed available to settlements is less than the area of land that can be cultivated by settlements’ “strong workforce”.

STRATEGY	NO. HOUSEHOLDS	MAX AREA- SOWING SEED	MAX AREA- LABOUR
SUBSISTENCE	one	3.98	6.80
	two	5.46	9.04
	three	6.96	12.28
	five	9.72	18.85
INTENSIFICATION	one	11.32	6.80
	two	15.46	9.05
	three	21.77	12.30
	five	31.31	18.98
EXTENSIFICATION	one	24.08	6.83
	two	34.54	9.03
	three	49.22	12.27
	five	78.15	18.99

Table 5.3. Maximum area of land that can be cultivated by the “strong workforce” available to settlements and maximum area of land that can be sown by sowing seed available to settlements with different number of households (year ≥ 50).

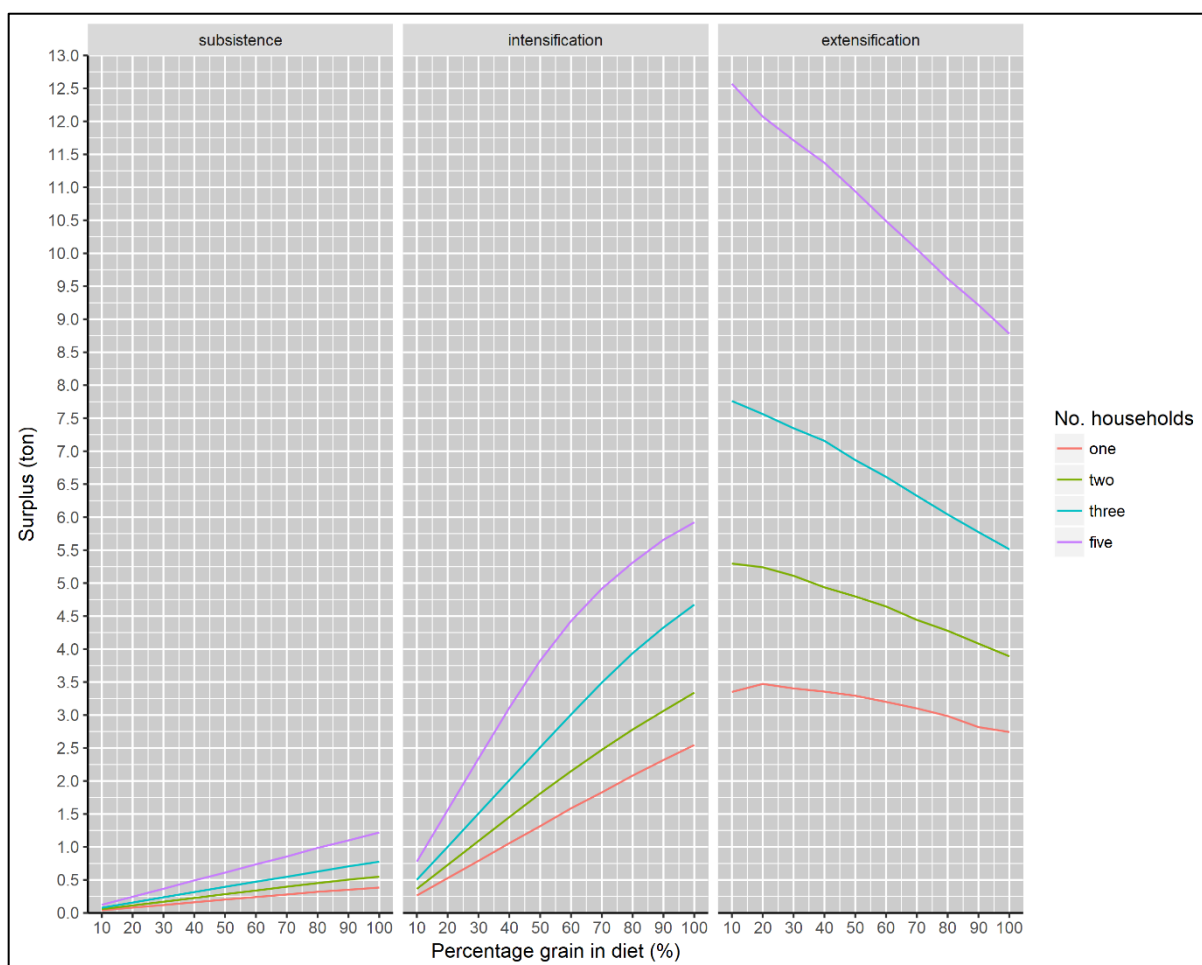


Figure 5.7. Surplus grain produced per settlement undertaking subsistence-based arable farming, intensification or extensification with different number of households with settlements producing a 50% buffer (year ≥ 50).

5.2.4. Summary

The results show that in subsistence-based arable farming, settlements are restricted more by the availability of sowing seed than by the availability of labour or the availability of land. Under subsistence-based farming, a small surplus of grain is available to settlements each year that would allow settlements to sow approximately twice the area of land than necessary (see figure 5.7). The area of land that can be cultivated by the available labour is much larger than the area of land necessary depending on the proportion of the diet that is grain-derived. The availability of labour remains constant regardless of the proportion of grain in the inhabitants' diet and so the difference between the area of land that can be cultivated and the area of land that needs to be cultivated reduces as the proportion of grain in the diet increases. As the proportion of grain increases, the minimum area of land that must be cultivated increases too resulting in a reduction of surplus labour. Although the area of arable land available to settlements in randomly-generated landscapes is not realistic, in these initial scenarios the availability of land is least limiting. In randomly-generated landscapes therefore, settlements are most limited by the availability of sowing seed. As settlements practicing subsistence-based arable farming do not aim to produce a large surplus of grain, it is not unexpected that settlements do not produce substantially more sowing seed than required.

If settlements produce a buffer of at least 50%, they are able to cultivate enough land to produce sufficient grain for consumption, sowing seed for the following year and a buffer. The land, labour and sowing seed available to settlements does not restrict subsistence-based arable. Whilst previous research has assumed 67.5% of the diet of the local population in the Dutch *limes* zone was derived from grain (Kooistra 1996, 70-73; van Dinter *et al.* 2014, 45-49), rural farmers were not necessarily restricted to this. Only very small deficits are experienced on average by settlements, but deficits do increase marginally when inhabitants are vegetarian i.e. 100% of the required calories come from crops (see figure 5.8).

Although settlements do not aim to cultivate any more surplus grain than a small buffer, a further surplus can still be produced when grain yields fluctuate above the mean basic yield of 1000kg/ha. A larger surplus is produced on average each year when settlements derive more calories from grain. With higher proportions of the diet based on grain, the area of land cultivated increases. This in turn increases the potential quantity of surplus each year. For the same reasons, the surplus grain produced by larger settlements is greater than the surplus grain produced by smaller settlements (see figure 5.7). Each year a mean surplus of between 40kg and 1219kg can be produced by settlements depending on the number of households and the proportion of the inhabitants' diet derived from grain. The former quantity is the mean annual surplus produced by single household settlements with inhabitants deriving 10% of their diet from grain; the latter quantity is the mean annual surplus produced by settlements with five households with inhabitants deriving 100% of their diet from grain.

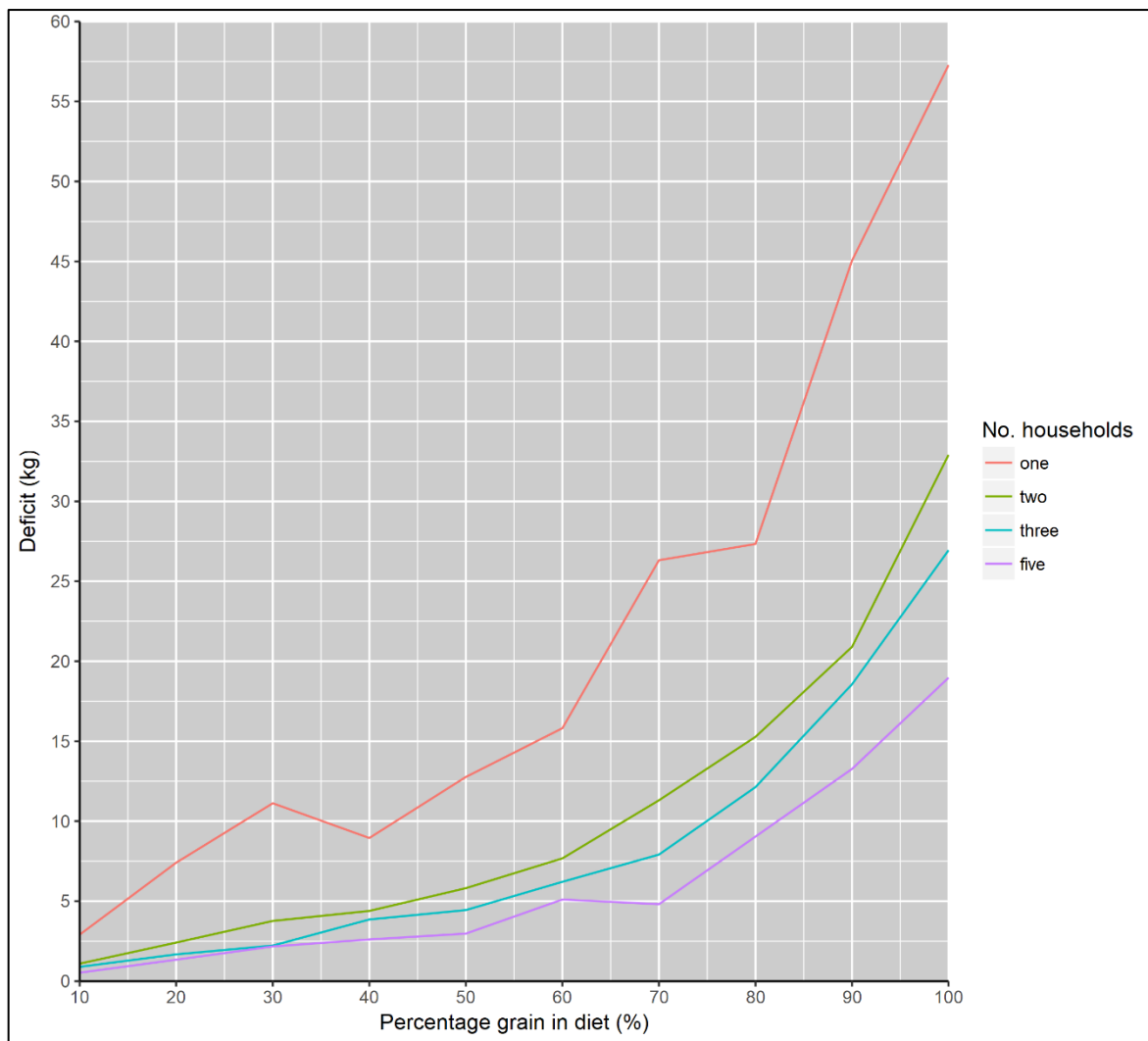


Figure 5.8. Grain deficits per settlement practicing subsistence-based arable farming with different number of households in scenarios with different proportions of grain-derived calories (year ≥ 50).

5.3. Animal husbandry

In ROMFARMS, different strategies of exploitation for the variety of products that livestock can provide to settlements are simulated by grouped mortality rates for different age categories of animals. In chapter 2, the evidence for animal husbandry in the Lower Rhine delta from the Late Iron Age to the Middle Roman period was discussed. Whilst cattle had an important role as demonstrators of wealth or use in gift exchange (Roymans 1999) and therefore the number of cattle were important, Filean (2006) argued that meat production may also have been an important, albeit secondary, product. Sheep/goat were exploited mostly for meat and perhaps milk in the period before Roman occupation (van Dijk & Groot 2013; Groot 2008a). However, although trends have been identified, Groot (2016) noted that there remained variety in the ways in which animals were exploited by settlements throughout the Late Iron Age and Roman period. Accordingly, a variety of exploitation strategies were simulated in the initial experiments of subsistence-based animal husbandry.

5.3.1. Strategies of exploitation compared

Owing to different mortality rates for animals of different ages in each exploitation strategy, the herd size and herd composition differ. This has an impact on the land and labour costs for the maintenance of livestock herds which are discussed here.

SPECIES	STRATEGY	NO. HEADS
SHEEP	meat	30.60
	milk	34.68
	wool	36.38
CATTLE	meat	54.14
	milk	65.60
	manure	27.04
HORSE	-	51.93

Table 5.4. Herd sizes of simulated cattle, sheep and horse herds.

5.3.1.1. Population size, composition and growth

Comparisons of population size indicates that an individual simulated cattle herd exploited for meat or milk contains more heads of cattle than a herd exploited for manure (see table 5.4). The size of a herd exploited for milk is in excess of the size of a herd exploited for meat with a mean 53 heads of cattle in the latter herds and 59 heads of cattle in the former herds. Cattle exploited for manure comprise approximately 27 heads of cattle. In cattle herds exploited for meat and milk, immature and young animals are disproportionately slaughtered. Larger herd sizes, in particular large numbers of adult animals, are needed to increase the birth-rate of the herd. This prevents the extinction of the herd in face of high slaughter rates of young and immature adults. The difference in herd sizes of sheep are small under all strategies of exploitation but is statistically significant (see table 5.4). Sheep herds exploited for wool contain the most heads of sheep with an average of 36 animals per herd and sheep herds exploited for meat contain the fewest animals with an average of 30 animals. Sheep herds exploited for milk comprise an average of 35 animals.

SPECIES	STRATEGY	YOUNG	IMMATURE	ADULT
SHEEP	meat	24.48	13.02	62.49
	milk	15.47	14.74	69.79
	wool	22.72	17.46	59.82
CATTLE	meat	19.39	16.23	64.38
	milk	10.90	20.76	68.34
	manure	15.54	30.53	53.93
HORSE	-	17.81	11.43	70.77

Table 5.5. Herd composition (%) of simulated cattle, sheep and horse herds.

Analysis of the age composition of cattle and sheep herds show that under all three strategies, adult animals form the largest part of the herd. The ratio of adult, immature and young animals differs however depending on the strategy (see table 5.5). When cattle are exploited for meat the majority of animals are slaughtered between ages 1 and 3 (immature group) in order to supply prime meat. Any animals that survive to adulthood are not slaughtered to prevent the extinction of the herd. As a result, young animals outnumber immature animals with both outnumbered by adult animals. In cattle herds exploited for milk, young animals are disproportionately slaughtered, and any surviving immature ones are not slaughtered to ensure sufficient number of cattle mature to adulthood. Adult animals are also not targeted as these

animals supply milk. Accordingly, in cattle herds exploited for milk, immature animals outnumber young animals. Slaughter rates for cattle exploited for manure are more uniform and do not target one age group disproportionately. However, given that animals mature relatively quickly (after 3 years) and that mortality rates are relatively low, adult animals outnumber immature animals which are more numerous than young animals.

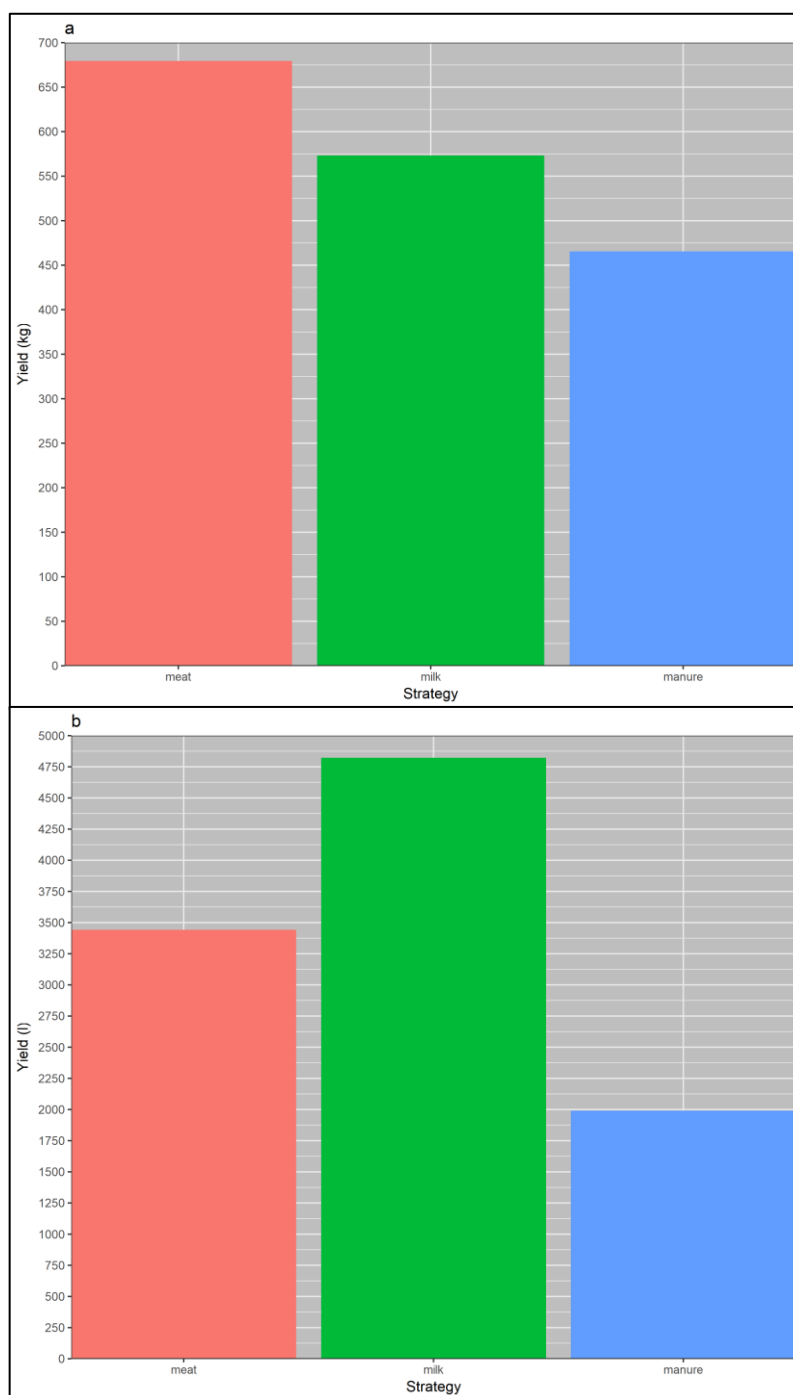


Figure 5.9a-c. Annual yields from simulated cattle herds exploited for meat, milk or manure (year ≥ 25); a) meat, b) milk & c) manure.

Among sheep herds, adult animals outnumber young and immature animals in all strategies (see table 5.5). In all strategies, young animals outnumber immature animals also. The fecundity of sheep and the ability for sheep to produce twin offspring results in a large number of young sheep each year. Accordingly, the number of young animals still outnumber, albeit marginally, immature animals despite being slaughtered disproportionately. In scenarios where sheep are exploited for meat or wool, slaughter rates for immature animals are higher than for young animals.

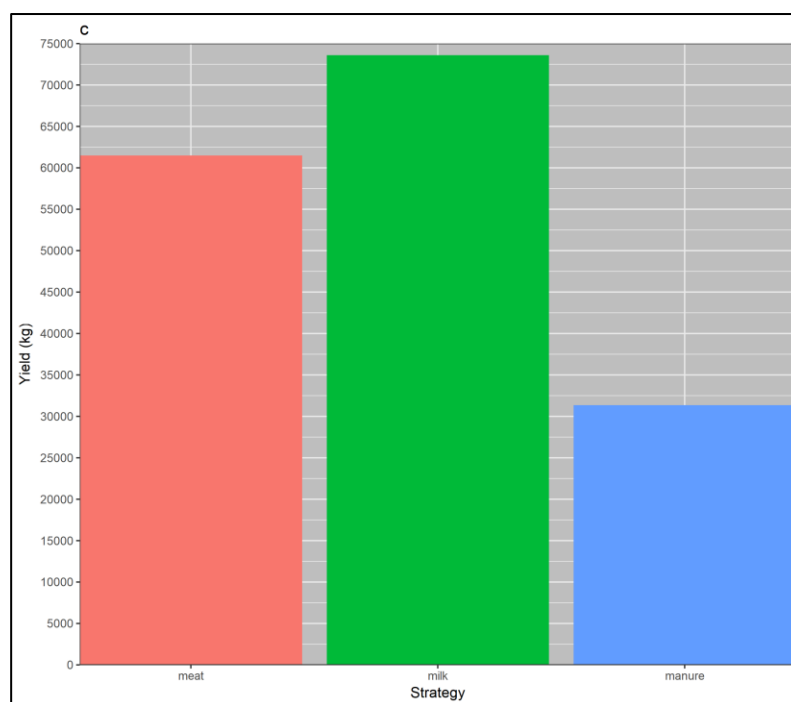
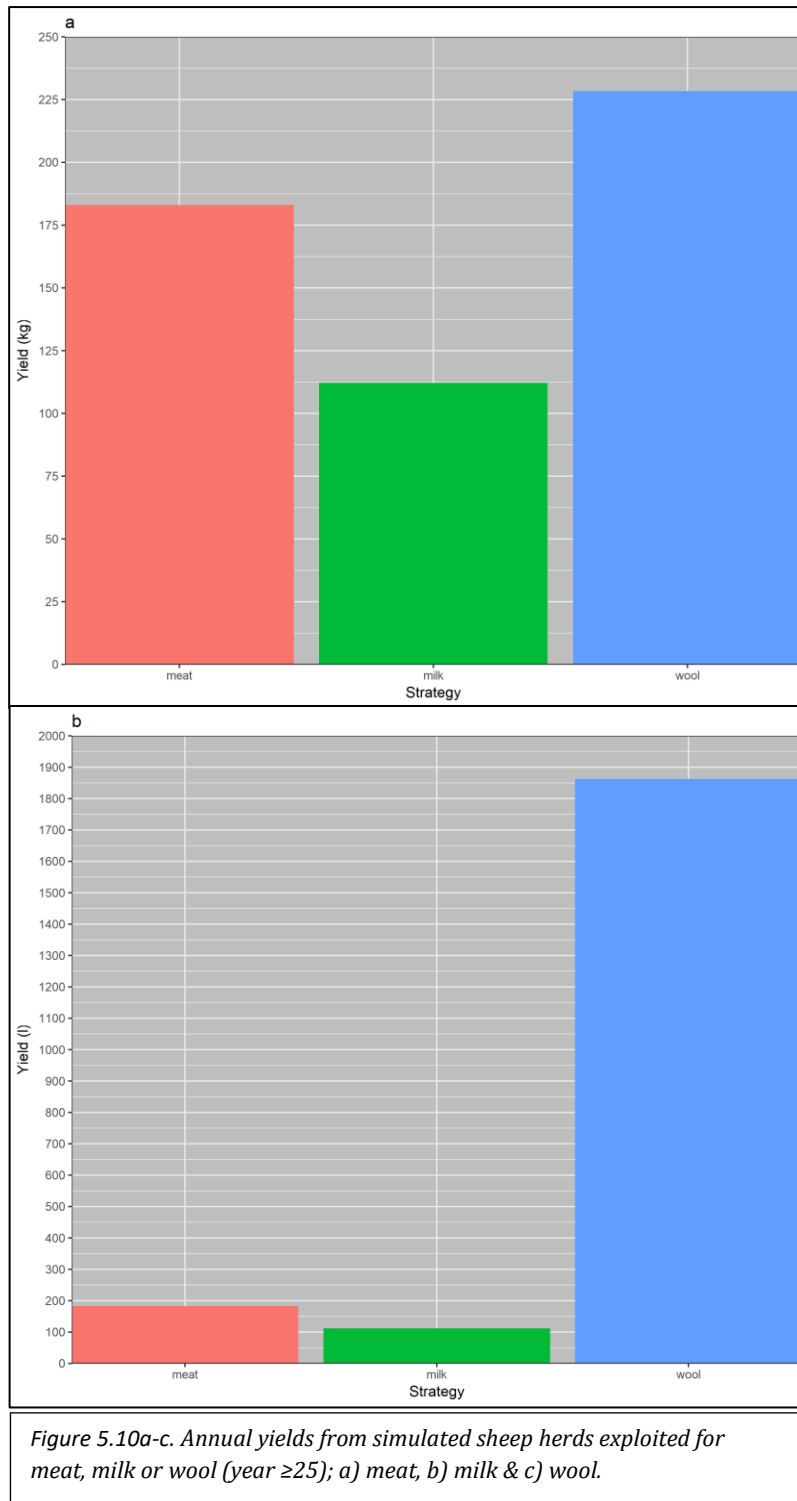


Figure 5.9a-c (contd.). Annual yields from simulated cattle herds exploited for meat, milk or manure (year ≥ 25); a) meat, b) milk & c) manure.

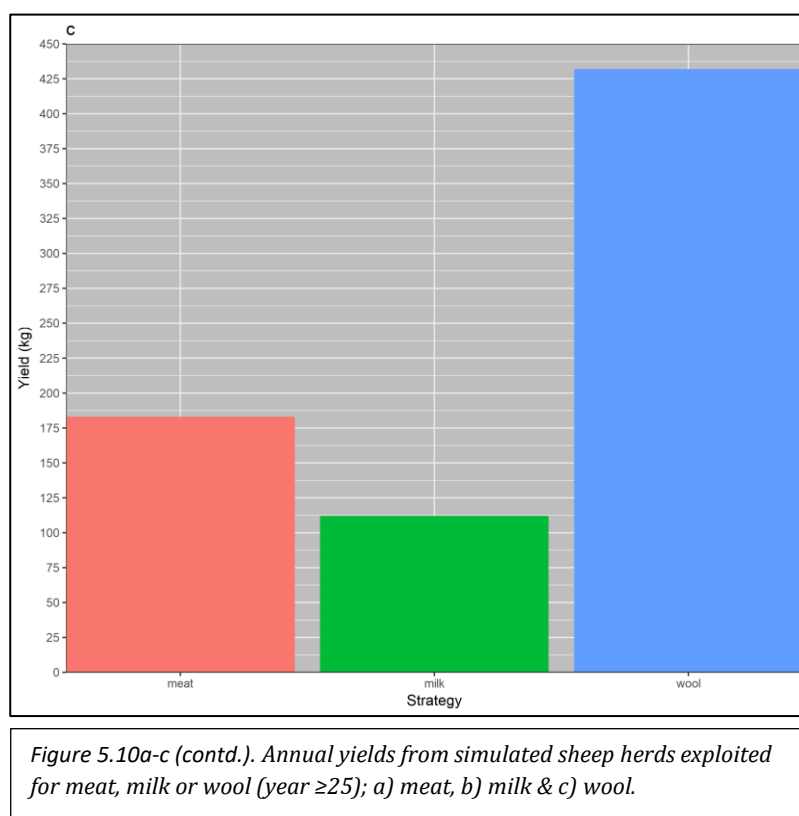
5.3.1.2. The supply of products

The quantity of meat, milk, wool (from sheep) and manure (from cattle) provided by sheep and cattle herds differs in scenarios when settlements exploit animals for different products (see figures 5.9a-c & 5.10a-c). Meat yield is highest from cattle herds exploited for meat followed by herds exploited for milk and with meat yields from herds exploited for manure lowest. This is not unexpected owing to the slaughter rates associated with different exploitation strategies. Mostly young animals are slaughtered when cattle are exploited for milk which provide little meat and few animals are slaughtered when cattle are exploited for manure. Settlements exploiting cattle for meat slaughter immature animals to increase meat yield and, although adult animals provide more meat than immature animals, immature animals provide more meat than young animals.

Similarly, in line with expectations, milk yields from cattle herds exploited for milk are highest among the three strategies simulated in ROMFARMS. The disproportionate slaughter of young animals ensures that high quantities of milk are available from herds exploited for milk. Whilst milk is not the primary product from cattle herds exploited for meat or manure, the larger size of herds exploited for meat results in a larger potential milk yield. Contrary to expectations, the yield of manure is lowest from cattle herds exploited for manure. Herds exploited for meat and milk are larger than herds exploited for manure and there is therefore a greater potential manure yield from these herds.



Among sheep herds, product yields conform somewhat to what was expected from the proportion of animals from different age groups that are slaughtered each year. Wool yields are highest from sheep herds exploited for wool although yields do not differ significantly. Milk yields are highest from herds exploited from milk and lowest from herds exploited for meat. Meat yields from sheep herds exploited for wool are higher than from herds exploited for meat. This is because more adult animals are slaughtered in herds exploited for wool than for meat whereas exploitation for meat focuses on immature animals. The meat yield from adult animals is greater than from immature animals, whereas immature animals supply prime-meat.



5.3.1.3. Sufficiency of calories supplied

It is assumed that in a mixed-agricultural strategy that ROMFARMS simulates only part of the calories required by the inhabitants of settlements is derived from grain. The remaining part is derived from animal products. Although van Dinter *et al.* (2014) assumed that only 67.5% of the calories required by each person were derived from grain, it was shown that settlements are able to cultivate enough land to allow for grain to comprise a larger proportion of the inhabitants' diet. It is therefore necessary to simulate subsistence-based agricultural strategies whereby grain consumption is not a fixed proportion. Accordingly, an important element of the analysis of animal husbandry is evaluating the different strategies of exploitation for the quantity of calories supplied and whether these are sufficient to fulfil the deficit that grain does not supply.

The total calories available from meat and milk supplied by a single simulated herd of cattle or sheep under each exploitation strategy are provided in figure 5.11. Despite a higher yield of meat from cattle herds exploited for meat, the higher milk yield from herds exploited for milk result in a higher yield of calories. The calories supplied by herds exploited for manure are lower than for the other two exploitation strategies given the low milk and meat yields. Smaller meat and milk yields per animal ensures that the total calories from meat and milk available each year from sheep herds are consistently lower than those available from cattle herds. Calories supplied annually from sheep herds are highest from those exploited for wool as a result of the higher meat yield from these herds. The high milk yield from sheep herds exploited for milk also results in relatively high calorie returns. Both a lower milk and meat yield from sheep herds exploited for meat result in the lowest calorie return among the three strategies of exploitation for sheep.

Whether animal herds can supply a sufficient amount of calories that the inhabitants of a settlement require after grain consumption is dependent on the proportion of the diet of a settlement's inhabitants derived from grain. Inhabitants deriving only 10% of the diet from grain will require a greater proportion of animal products in their diet than if 90% of the diet comprised grain. The remaining calories required by settlements after grain has been consumed are

provided in figure 5.11. In addition, figure 5.11 provides the mean combined calories from meat and milk from individual cattle and sheep herds under different exploitation strategies. The results show that if any of the total calories required by the inhabitants are derived from sheep herds, settlements of all sizes would not be able to derive sufficient calories from a single sheep herd under any of the three exploitation strategies.

The potential yield of animal products from a single cattle herd is sufficient in some scenarios to provide settlements with enough calories to make up the deficit left after consumption of grain. The lower output of animal products from cattle herds exploited for manure reduces the number of scenarios in which these herds provide sufficient calories. Settlements comprising one, two, three or five households can not depend on cattle herds exploited for cattle for more than 60, 40, 30 or 20% respectively of the total calories required by their inhabitants. Animal products from cattle herds exploited for other products (meat and milk), can supply sufficient calories for settlements in more scenarios. Large settlements with three or five households can not depend on a single cattle herd exploited for meat or milk, unless the proportion of grain in the diet of inhabitants is more than approximately 50% or 70% respectively. Smaller settlements with two households can be supplied with up to 70 or 60% of the required calories by cattle herds exploited for milk or meat respectively. For the smallest settlements comprising a single settlement, a single cattle herd exploited for meat or milk can supply sufficient calories regardless of the proportion of the inhabitants' diet that is grain-derived.

If the assumption made by van Dinter *et al.* (2014; see Kooistra 1996, 70-73) that 67.5% of the diet of inhabitants in settlements was derived from grain reflects a realistic historical situation in the Dutch *limes* both before and after Roman occupation, a single herd of cattle exploited for meat or milk can supply a settlement with the remaining 22.5% of the total calories required by settlements. The remaining 10% are assumed to come from diverse wild sources such as fish, wild mammals and birds, and wild plants and fruit. Cattle exploited for manure can also provide sufficient animal products to supply 22.5% of the total calories required by a settlement for settlements with one, two or three households. Settlements with five households need to manage at least two cattle herds exploited for manure if 22.5% of the diet comes from animal products. However, this would entail extra land and labour costs. The calories supplied by sheep herds are so few however that up to eight sheep herds would need to be kept by settlements with five households to fulfil 22.5% of the total calories required. Even for the smallest settlements with one household, at least three sheep herds would be required.

Whether the yields from differently managed sheep and cattle herds are sufficient for the needs of settlements are based on each settlement managing one of the herds as simulated by ROMFARMS. This is because the basic unit of livestock used in ROMFARMS is the herd which emerges from the combination of natural mortality rates and slaughter-rates determined by an exploitation strategy. The discussion in this section argues that if settlements can not produce sufficient animal products from one herd, more animals can be kept. The calculations for outputs from more animals are based on the outputs of multiple herds identical to the individual herds that are simulated by ROMFARMS. The discussion refers therefore to settlements keeping multiple herds. It is perhaps more realistic to base calculations on larger herds instead of multiple herds, however. To do so would require settlements to practice different animal husbandry strategies than simulated, such as employing different slaughter rates or changing the initial herd size. An alternative strategy could be collective management of large herds by multiple settlements. These strategies have not yet been implemented in ROMFARMS so far. The discussion below argues also that the outputs from some herds simulated by ROMFARMS are more than needed by the smallest settlements simulated. The relatively large herd sizes that

emerge from simulations are unlikely to be realistic representations of actual herd sizes kept by very small settlements in the past. Different animal husbandry strategies that are not yet simulated in ROMFARMS could result in smaller herds of animals for example. In ROMFARMS, the exploitation strategies simulated and the population sizes and product yields that emerge from the strategies represent only limited possibilities within the range of animal husbandry strategies that could be available to settlements in the past.

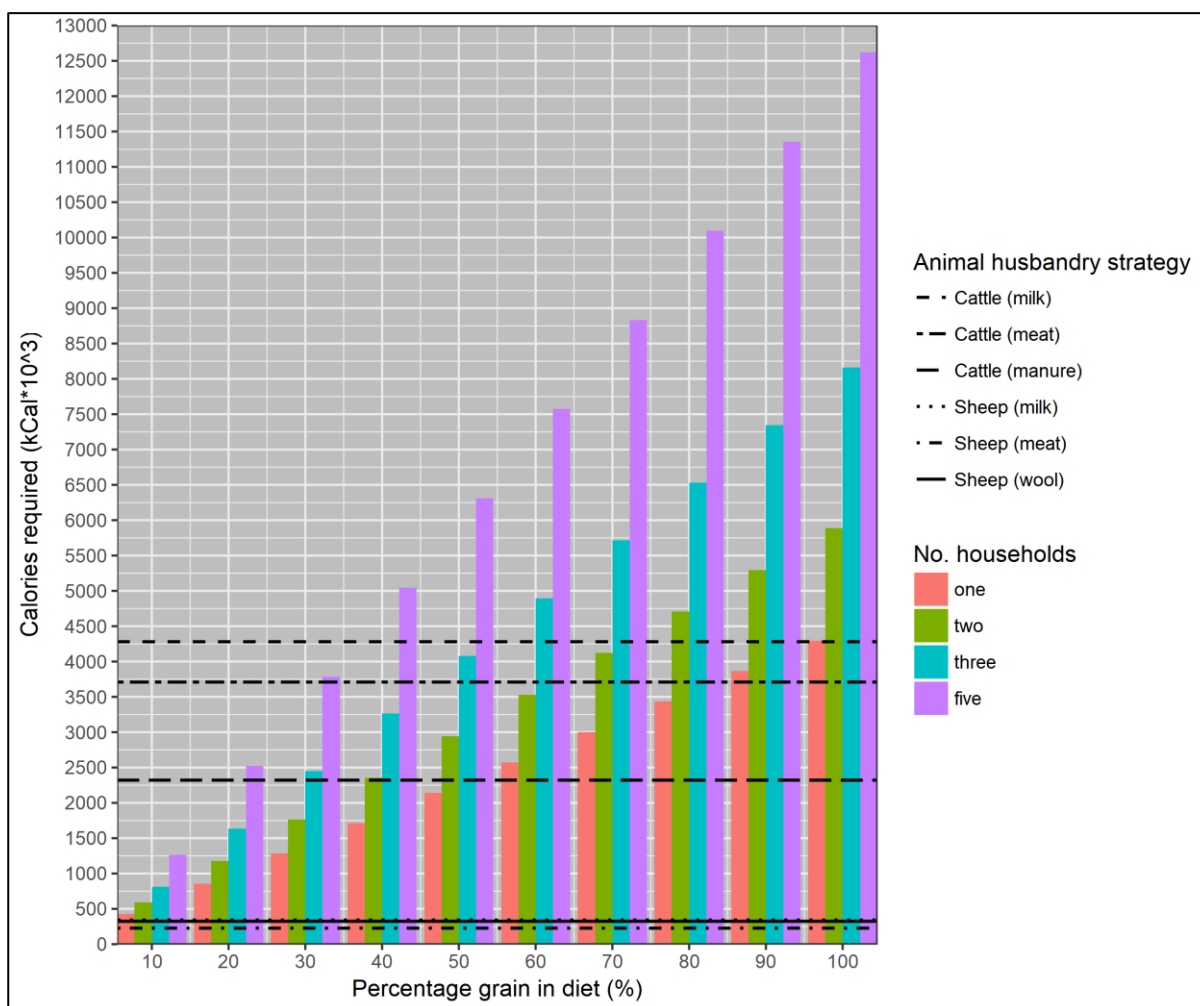


Figure 5.11. Annual calories required by settlements with different numbers of households from animal products (bars); mean annual total calories from cattle and sheep herds under different exploitation strategies (lines).

5.3.2. Limiting factors

Settlements keeping cattle and sheep herds need access to pasture and meadow land and must have available labour to produce winter fodder for animals. In addition, animal husbandry is limited by the dynamics of the herd which are determined both by the rate of slaughter and by biological factors, namely natural mortality and the birth rate of the herd. Whilst the dynamics of the herd limits the yield of products from the herd, the land and labour costs determine whether a particular exploitation strategy is viable.

5.3.2.1. Availability of land

It is assumed in ROMFARMS that livestock herds require an area of pasture land each year for the majority of the year and an area of meadow land necessary to produce fodder for a four-month winter when food for animals is scarce in pasture (see chapter 4 section 4.3.5). The areas required

for pasture land i.e. land for animals to graze upon for the majority of the year and meadow land i.e. land for the production of hay as well as the labour costs for production of fodder are presented in table 5.6. It is assumed that both pasture and meadow land were located in flood basins. There is limited evidence for this. The presence of wetland and marsh plants within archaeobotanical assemblages recovered from within some rural settlements including from mineralized manure points to the use of flood basins for pasture and fodder collection, or both (Groot & Kooistra 2009). Undoubtedly, labour costs for the maintenance of animal herds comprised more than the labour required for fodder production. The limitations of available data to use as assumptions plays a role here. It is assumed however that the daily labour costs in animal husbandry were very minimal in comparison with hay production. Therefore, the only labour cost associated with animal husbandry used in ROMFARMS is the production of fodder.

The land required for animal herds is greater than that required for arable farming. The land required, however, differs depending on strategy as this has influence on the size of the herd. Furthermore, there are differences between the area of pasture land and meadow land required within strategies given the differences in both the area of pasture and meadow land required per animal and that herd size differs at times of the year. According to assumptions used in ROMARMS an adult cow requires 0.08ha more pasture land than meadow land, and an adult sheep requires 0.03ha more pasture land than meadow land. Furthermore, in ROMFARMS, slaughter occurs at the beginning of winter and therefore herd sizes are larger before this. Animal herds require pasture land before the winter and therefore the larger herd size during this time results in a greater demand on pasture land.

SPECIES	STRATEGY	PASTURE & MEADOW LAND REQUIRED (HA)	LABOUR REQUIRED FOR FODDER PRODUCTION (HRS)
SHEEP	meat	4.88	31.50
SHEEP	milk	5.71	39.11
SHEEP	wool	5.89	37.75
CATTLE	meat	27.10	172.90
CATTLE	milk	31.40	207.92
CATTLE	manure	14.16	89.03
HORSE	-	24.86	171.28

Table 5.6. Land and labour costs for simulated cattle, sheep and horse herds.

The total area of land is dependent on the size of the herd and thus cattle herds exploited for milk require the greatest area of land and marginally in excess of the area of land required by herds exploited for meat. Cattle exploited for manure results in the smallest herds size and therefore the smallest area of land required. Land costs for sheep herds are relatively similar owing to the similarity in herd sizes under all three exploitation strategies. Variation in the requirement for pasture and meadow land can be attributed again to small differences in total herd size. Hence, sheep herds exploited for wool require the greatest area of pasture and meadow land but only marginally more (0.18ha) than herds exploited for milk. Sheep herds exploited for meat possess the lowest number of heads and accordingly, the smallest area of land.

5.3.2.2. Availability of labour

Keeping livestock herds require the expenditure of labour by settlements for the production of fodder for animals during winter. The total labour expenditure per herd is dependent therefore on the area of meadow land that must be mowed each year for hay production.

For the simulated cattle herds, the area of meadow land required for fodder production and therefore the total labour expenditure corresponds with total herd size (see table 5.6). Accordingly, the quantity of fodder needed by cattle herds exploited for milk is higher owing to larger herd size and therefore the labour for fodder production is highest (see section 5.3.1.1 this chapter for the sizes of herds as simulated in ROMFARMS). As herd sizes of cattle exploited for manure are smallest, they require the least amount of fodder for winter and therefore labour expenditure is lowest. For sheep herds, labour expenditure does not always correspond to herd size. Sheep herds are larger when sheep are exploited for wool however labour expenditure is marginally less than when sheep are exploited for milk (a difference of c. 1.36hrs). Despite sheep herds exploited for wool requiring a greater total area of land than herds exploited for milk, the area of meadow land required is less (see table 5.6). This is owing to the herd composition: a sheep herd exploited for milk contains more adult animals than a herd exploited for wool and adult animals require more fodder than immature or young animals.

SPECIES	STRATEGY	NO. HOUSEHOLDS			
		ONE	TWO	THREE	FIVE
SHEEP	meat	23.84	30.99	41.77	64.44
SHEEP	milk	19.20	24.95	33.64	51.89
SHEEP	wool	19.90	25.85	34.85	53.76
CATTLE	meat	4.34	5.64	7.61	11.74
CATTLE	milk	3.61	4.69	6.33	9.76
CATTLE	manure	8.44	10.96	14.78	22.80

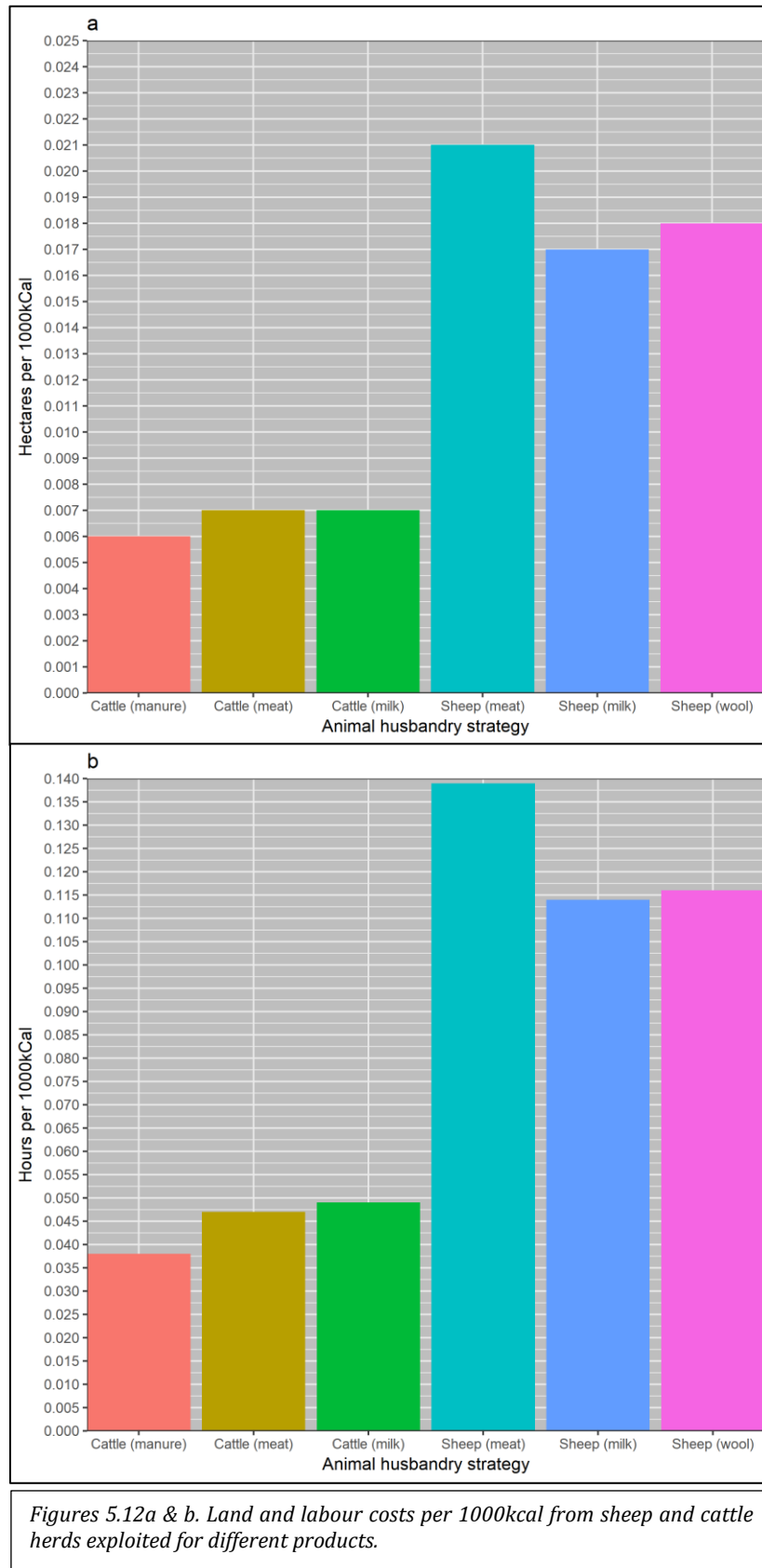
Table 5.7. Maximum number of simulated cattle and sheep herds that can be maintained by settlements of different sizes with available labour as limiting factor.

As with arable farming, the labour pool for the production of fodder for animals in the winter is limited as only the “strong” workforce (adult men and women) can undertake this agricultural task. The results show that settlements are not limited by labour in the maintenance of individual herds. In those scenarios where settlements can not derive sufficient calories from animal products, there is enough surplus labour to produce fodder for multiple herds. Owing to the smaller area of land sheep herds require, settlements of all sizes are able to keep a relatively high number of sheep herds (see table 5.7). The number of cattle herds that settlements can keep is more limited, however, settlements have sufficient labour to maintain enough extra herds of cattle to produce sufficient yields of milk and meat required by the inhabitants. Accordingly, in subsistence animal-husbandry, settlements can maintain more animal herds than are needed.

5.3.3. Summary

Different animal husbandry management practices exploiting cattle and sheep for different products results in different herd sizes and, to a lesser degree, differences in herd composition. Adult animals dominate but the proportion of immature and young animals within different herds varies as a result of different slaughter rates. The size and composition of a herd are the principal determinants of the yield of products available from herds and the land and labour costs associated with their maintenance. Although sheep herds exhibit only small differences in herd sizes between the different exploitation strategies, the herd sizes of cattle exploited for meat or milk and herds exploited for manure differ significantly. It was noted earlier that different interpretations of cattle management practices have been present in previous research relating to the subsistence-based animal husbandry of the Late Iron Age in the Lower Rhine delta. Whilst Roymans (1999) suggested that cattle played an important role as wealth indicators, Filean (2006) argued that meat too may have been an important secondary product. Unexpectedly, the

results have shown that large herd sizes emerge from a strategy exploiting cattle meat. Therefore, the exploitation of cattle for meat and managing cattle herds to maximise numbers of heads in a herd are not mutually exclusive and both goals can be achieved concurrently.



The yields of animal products from cattle and sheep herds differ too among the strategies of exploitation. The results show that different exploitation strategies of sheep have a reduced impact on the availability of products. The yields of meat and milk from sheep herds are minimal however and it is unlikely that, unless the inhabitants of settlements depended on animal products for only a very small part of the diet or kept very many herds, sheep were the primary source of calories for farmers. When settlements derive from animal products a relatively high proportion of the diet however, settlements must manage more animals than can be found in an individual herd of cattle simulated by ROMFARMS. In this discussion, outputs from more animals are calculated based on the estimated yields of multiple modelled herds rather than larger herds. It was also assumed that each settlement managed their own livestock. Collective management of animals by several small settlements is another potential animal husbandry strategy that is not explicitly modelled in ROMFARMS.

The possible importance of milk as a source of calories is conspicuously absent in previous landscape capacity models of the rural economy in the Dutch *limes* zone. Van Dinter *et al.* (2014) only included the calories available from cattle meat within their calculations of rural production of animal products for example. This is despite the recognition of cattle being kept for milk and meat production. The results show, however, that milk produced by cattle herds under all exploitation strategies is significant and without the consumption of milk, or dairy products such as cheese, the calories supplied by meat available from single cattle herds is insufficient in more scenarios than when both milk and meat are consumed.

The land and labour costs are significantly less for sheep herds than those associated with the maintenance of cattle herds. This would appear to confirm a suggestion from Groot (2008a) that keeping sheep herds would have been preferred by farmers in the past when the number of animals that could be kept was limited. Although the results from this simulation show that sheep herds require less land and labour, as discussed above, the total calorie return is also reduced. The costs in land and labour per 1000kCal are provided in figures 5.12a & b and show that per 1000kCal gained from cattle herds required, a smaller area of land and fewer hours are required. The labour pool available to settlements was sufficient to keep more animals than in a single modelled herd. Under subsistence-based animal husbandry, the availability of labour does not appear to have restricted settlements' ability to produce enough animal products for their own consumption.

5.4. Fuel collection

In addition to food producing agricultural tasks, settlements must also undertake the collection of fuel throughout the year for cooking and keeping warm. The total amount of fuel required by a settlement is determined by the number of inhabitants and the per capita fuel consumption determined by the parameter "*daily-per-capita-fuel-use*". In addition, the frequency with which fuel is collected from the landscape determines the quantity of fuel that is needed each time a settlement collects fuel. If fuel is collected less frequently than every day, enough fuel must be collected for the days between collections. The source of fuel in the Dutch pre-Roman and Roman *limes* zone has already been discussed in chapter 2 (section 2.7) and was very likely to have been wood. The landscape of the *limes* zone had already been significantly deforested by the time of the Roman occupation (see chapter 2 section 2.4) although in the western region where the Cananefates were located, discontinuity in occupation may have resulted in regeneration of woodland (de Bruin 2017). The available labour for a settlement and the per capita consumption were all expected to be limiting factors within fuel collection.

5.4.1. Availability of labour

The collection of fuel can be undertaken by a wider labour pool than other agricultural tasks as the elderly and children between 10 and 15 can also be used in addition to adult males and females. However, because individuals are limited by how much they can carry per trip, it is expected that, despite the increased size of the labour pool, the availability of labour could restrict the ability for settlements to collect sufficient fuel each year. By simulating scenarios in which settlements collect fuel with different frequencies and in which per capita consumption of fuel differs, the possible fuel collection strategies that could have been successfully undertaken by settlements can be gauged in terms of demand on available labour.

Van Dinter *et al.* (2014) assume a daily per capita fuel use of 5kg for rural settlements which was used as a starting point to assess the availability of labour as a limiting factor of fuel collection strategies. The mean annual deficit of firewood from settlements consuming 5kg per person per day is provided in figure 22. The results show that as collection frequency reduces, the size of the deficit increases. When settlements collect fuel less frequently, the amount of firewood they must collect on each trip is greater. The inhabitants of a settlement can not collect large amounts of firewood owing to restrictions on the maximum load they can carry. Therefore, settlements of all sizes consuming 5kg per person per day will need to undertake daily collection of firewood to avoid significant deficits according to limitations placed on them by the availability of labour.

Fuel collecting behaviour is also determined by the consumption rate per person in a settlement, however. The mean annual deficit of firewood for settlements when the inhabitants consume between 1 and 10kg of firewood per person per day and with different frequencies of collecting firewood is provided in figure 5.13. If settlements reduce per capita consumption, collection frequencies can be reduced owing to the reduction in the total amount of firewood required for each trip. The results also show a maximum consumption rate for settlements of different sizes. Consumption of more than 7kg would result in significant deficits even when settlements collect fuel every day. Given that settlements can not collect fuel more frequently than once per day in ROMFARMS, it is assumed that the availability of labour caps per capita consumption.

5.4.2. Availability of wood

Whilst van Dinter *et al.* (2014) provided substantial calculations for the demand of both native rural settlements, and military settlements and *vici*, the calculations were based on a fixed per capita consumption of 5kg per day in rural settlements and a settlement size of 1.5 households. However, as discussed above, settlements are capable of consuming more or less than 5kg per capita per day.

It is not possible to accurately reconstruct the availability of woodland or firewood available in landscapes of the past. However, it can be assumed that if available wood falls below the minimum required, settlements will be limited in the quantity of wood they can collect and would need to seek secondary sources of fuel e.g. fuel from fenlands or peat fuel. Given that the landscape of the Lower Rhine delta was already mostly deforested in the Late Iron Age (Groot & Kooistra 2009; Kooistra *et al.* 2013), it is not unrealistic that the availability of wood may have been limited. There would have been regional differences in the availability of woodland with the western region of the Cananefates already mentioned although these have not been simulated in the randomly generated landscapes. The total quantity of fuel required, despite the difficulty in quantifying forest cover in the past, may not have been available in a deforested landscape.

5.4.3. Summary

Simulating different fuel collection strategies has revealed the likelihood that different fuel collecting behaviours could have enabled settlements to collect sufficient fuel to meet the demands of their inhabitants. Fuel collecting behaviour can be adapted by either changing the frequency in which settlements collect fuel or by increasing or decreasing the daily per capita consumption of inhabitants. Both increase or decrease the total quantity of fuel that settlements must collect per trip. Despite the labour pool for fuel collection being larger than the labour pool for other settlements with the elderly and adolescents over the age of 10 also able to collect fuel, the finite number of inhabitants and the restrictions on the maximum load that can be carried by inhabitants limits both the maximum rate of consumption and the minimum frequency that fuel can be collected. A per capita fuel consumption each day that exceeds 7kg results in significant deficits. Furthermore, settlements consuming more than 3kg per capita per day need to collect fuel each day to avoid deficits. Reduction of per capita fuel use can permit settlements to reduce the frequency of fuel collection, however settlements need to reduce fuel consumption to 1-2kg per capita if fuel is collected less frequently than once per three days. Per capita fuel consumption in the past can only be estimated and accordingly different consumption rates were simulated in experiments with the subsistence-based economy in ROMFARMS. However, if the assumption of van Dinter *et al.* (2014) that inhabitants of rural settlements used 5kg of firewood per day is realistic, then the optimal collection strategy is daily. Whilst settlements still, on average, experience a deficit of firewood, the mean deficit per settlement is negligible when compared with the total annual requirement. Daily collection of fuel to provide 5kg of firewood for settlements results in a significant labour expenditure, however. The total expenditure for all agricultural tasks for settlements of different sizes is provided in figure 5.14. Annually, labour expenditure for fuel collection exceeds the labour expended for other agricultural tasks: sowing, ploughing, harvesting or fodder collection. The size of the workforce settlements that use i.e. the number of inhabitants that were needed to go into the landscape to collect fuel, is on average smaller than the total size of the strong workforce available (see figure 5.14). Therefore, settlements undertaking an optimum strategy of daily collection of 5kg do not require the potential labour of children or the elderly. This is not the case when either larger quantities of fuel are consumed per day per capita or collection frequencies are reduced. In these scenarios, the mean size of the workforce used by settlements reaches or indeed exceeds the mean size of the labour pool available to settlements and only settlements with a labour pool in the upper quartile have a sufficiently large workforce, otherwise the settlement experiences a deficit of firewood.

The results indicate that settlements are significantly restricted in fuel collection by the availability of labour. The availability of labour places a cap on both the consumption rate of inhabitants and the frequency of collection. In randomly-generated landscapes, restrictions on the availability of firewood are not incorporated and therefore it is not possible in these experiments to identify whether the availability of firewood in the past would have had a limiting impact. However, the results do show the minimum quantity of firewood needed by all settlements occupying a landscape. In landscapes of the past, settlements would experience deficits unless they undertook wood management strategies or sought alternative fuel sources when the quantity of firewood naturally was lower than that required by the settlements occupying a landscape.

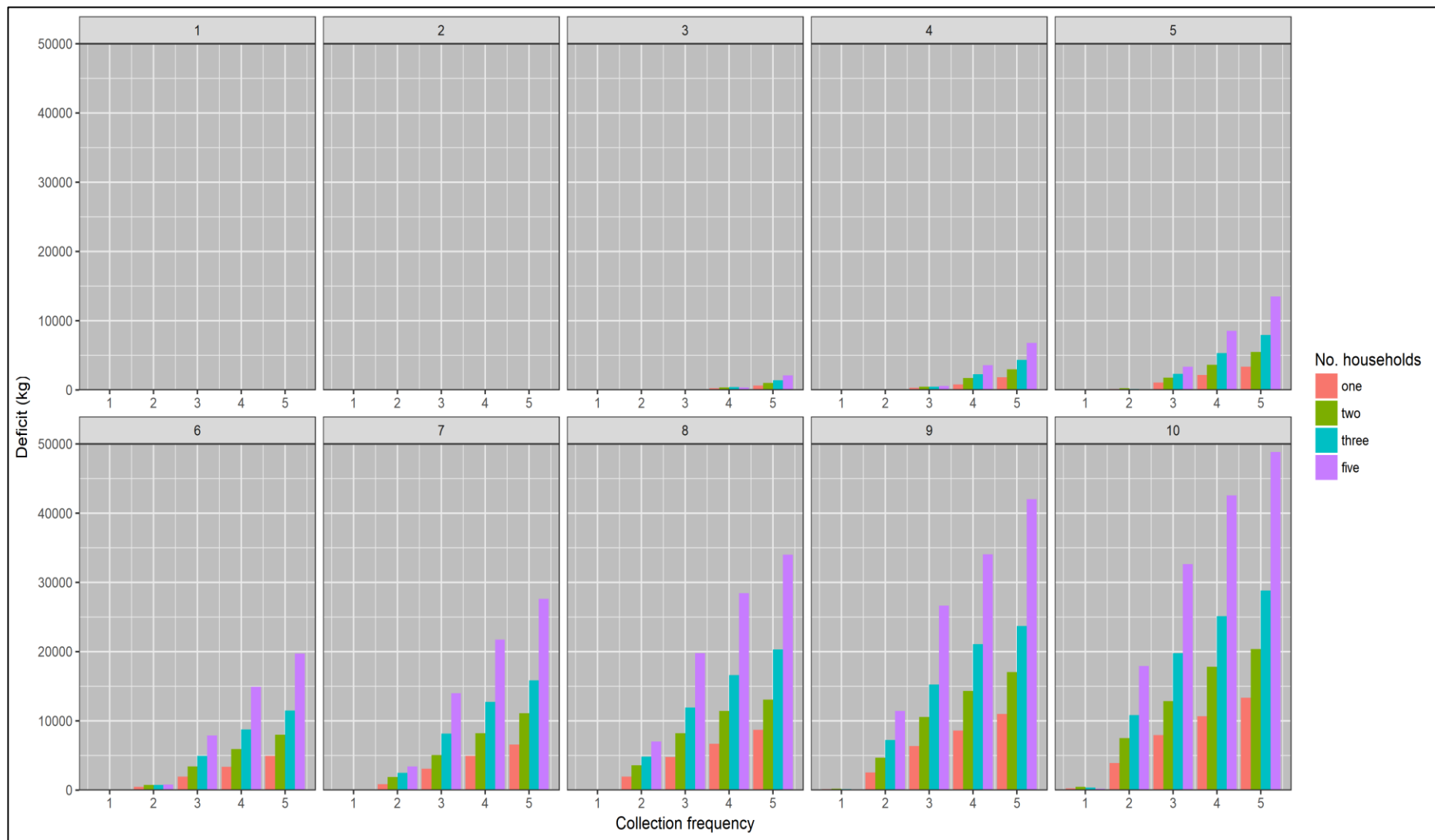


Figure 5.13. Mean annual deficit of firewood per settlement with collection frequencies of daily to 1x per 5 days (bars) and consumption of 1 to 10 kg per capita per day (panels) (year >=50).

5.5. Conclusion: optimal farming strategies in a subsistence economy

The above analysis of the agricultural activities of the subsistence-based economy assumed to have been practiced in the Lower Rhine delta prior to Roman occupation in the Late Iron Age, has revealed the land and labour costs necessary for settlements to produce sufficient food and collect sufficient firewood and timber for their inhabitants. In addition, the relative importance of the assumed limiting factors has been analysed to gauge the possible restrictions that small-scale agriculturalists in the region may have encountered. As detailed previously (see chapter 2 section 2.6), Late Iron age settlements in the Dutch *limes* region practiced subsistence-based agriculture. Settlements likely undertook a single cropping per year of emmer or barley and practised biennial fallow. Settlements also kept sheep and cattle herds, exploiting sheep for meat and, perhaps, also milk (Groot 2008a; van Dijk & Groot 2013). Wool would have been an important product too as indicated by the prevalence of loom weights and spindle whorls found in rural settlements (see for example the site catalogue in Willems 1986, 95-133). Cattle were exploited for meat but also to maximise the size of the herds to use cattle as a means of payment, a standard of value and wealth indicators (Filean 2006; Roymans 1996). Little evidence of any woodland management strategy exists for this period indicating that settlements collecting firewood and timber from whatever woodland that still remained naturally in the region in this period. The results of initial experiments in light of this probable agricultural strategy are summarised below.

5.5.1. The agricultural calendar

By analysing the labour costs for all agricultural tasks not only as total annual expenditure but also as monthly expenditure, periods of intensive labour expenditure can be identified within the agricultural calendar. Labour expenditure for each task was distributed throughout the year according to the period that agricultural tasks would take place with the majority of tasks having a strict window in which they must be completed. As winter sowing is assumed in ROMFARMS, September is assumed as the month in which ploughing and sowing were undertaken; for harvesting the following August. In July, settlements are required to collect winter fodder for animal herds. Every month settlements must also collect firewood. Although in certain months, expenditure is high for settlements of all sizes, there is sufficient time to undertake agricultural tasks within the allotted time windows with the workforces that emerges from simulations in each settlement (see figure 5.15). Furthermore, there is significant “downtime” in the agricultural calendar where labour costs are nil. Outside of peak periods of labour expenditure, labour input was generally low apart from the unending need to collect fuel regularly throughout the year. Underemployment in the agricultural calendar does not only affect simulated agriculturalists in ROMFARMS however but is a phenomenon of ancient agriculture in general (Erdkamp 1999; 2005).

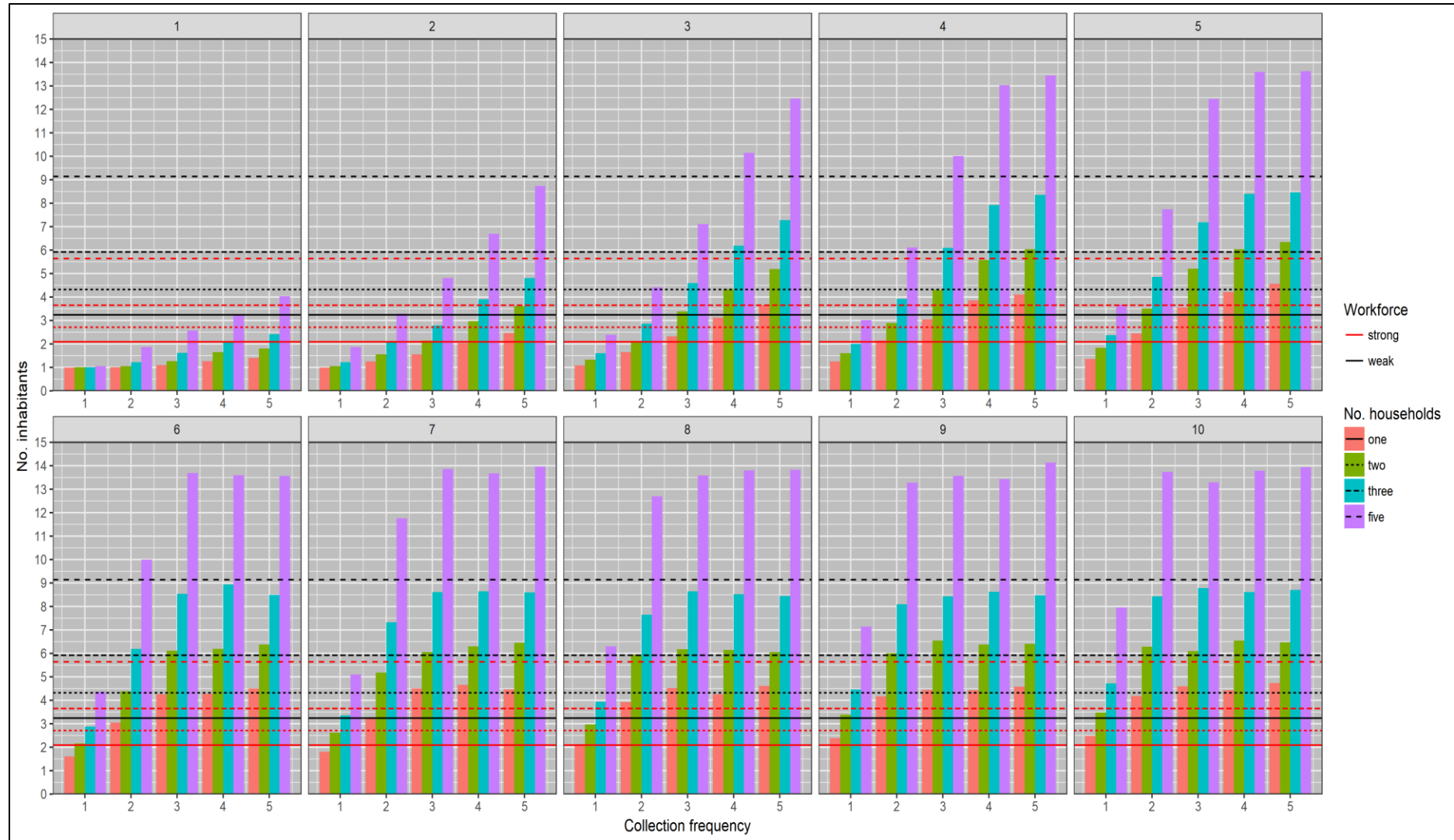


Figure 5.14. Size of workforce required for fuel collection (bars) with different collection frequencies and per capita fuel consumption (panels) vs. mean size of "weak" and "strong" workforces available to settlements of different sizes (lines).

5.5.2. Producing enough food, collecting enough wood

Experimenting with subsistence-based arable farming has shown that the settlements must cultivate a small surplus or “buffer” each year to produce sufficient food in years when grain yield falls below the average yield predicted by settlements. From the point view of simulation, without producing a buffer, when yields fall below the predicted average yield, settlements may not produce sufficient sowing seed for the following year which will prevent settlements from cultivating enough land. As a result, the deficit is even greater in the following year. If settlements however cultivate a buffer of 50% extra, they are protected from negatively fluctuating yields and will consistently be able to cultivate sufficient land to produce enough grain for the inhabitants to consume and sowing seed for the following year. Historically speaking, a “buffer” also served to protect against tribal warfare, small-scale raiding and other crises (Roymans 1996), as well as providing a commodity for small-scale exchange and barter networks.

Although others have assumed that settlements in the region during the Late Iron Age and Roman period would have derived more calories from grain than animal products, the results have shown that settlements were not restricted, as far as labour limits agricultural productivity, to consuming this proportion. Rather, settlements had available labour to cultivate sufficient land to produce grain to fulfil up to 100% of the diet of the inhabitants. If settlements are small or derive a majority of their diet from grain, the calories supplied from a single herd of cattle as modelled in ROMFARMS exploited for meat or milk are sufficient to fulfil the deficit remaining after grain consumption. When larger settlements derive a greater proportion of the diet from animal products however, this number of animals do not supply sufficient calories. The available labour from the “strong” workforce inhabiting larger settlements does not prevent the possibility of keeping more animals, however. Analysis of the dynamics of cattle and sheep herds have also revealed the possible herd structures of animal herds when exploited for different products. Most noteworthy are differences in herd size. Cattle herds exploited for manure stabilise with fewer animals whereas cattle exploited for meat or milk are larger. Accordingly, the Late Iron Age tradition of managing cattle to maximise the number of animals does not preclude exploitation for meat or milk.

Conversely, the availability of labour is strongly limiting for fuel collection. The size of workforce available to settlements restricts the number of strategies of fuel collection that do not result in significant deficits. Accordingly, settlements must collect fuel regularly and limit consumption. A consumption rate of 5kg as assumed by van Dinter *et al.* (2014) is possible but only if settlements collect firewood every day. When settlement consume smaller quantities of firewood, this can be collected less frequently. Settlements also experience a maximum limit of per capita consumption. Deficits increase as consumption increases even when settlements collect fuel daily.

The scenarios discussed above were simulated within a randomly-generated landscape with areas of levee, flood basin and a forest cover that is likely unrealistic and does not reflect the landscapes of the past in the Lower Rhine delta in the Late Iron Age. Accordingly, it is not possible within this discussion to analyse the impact that availability of land or woodland has on the ability for settlements to produce sufficient food or collect sufficient firewood. However, it can be expected that in landscapes when the areas of land required by arable and pastoral farming or the quantity of firewood required by settlements is insufficient, the availability of land and woodland would become limiting factors. This is discussed in more detail in chapter 7.

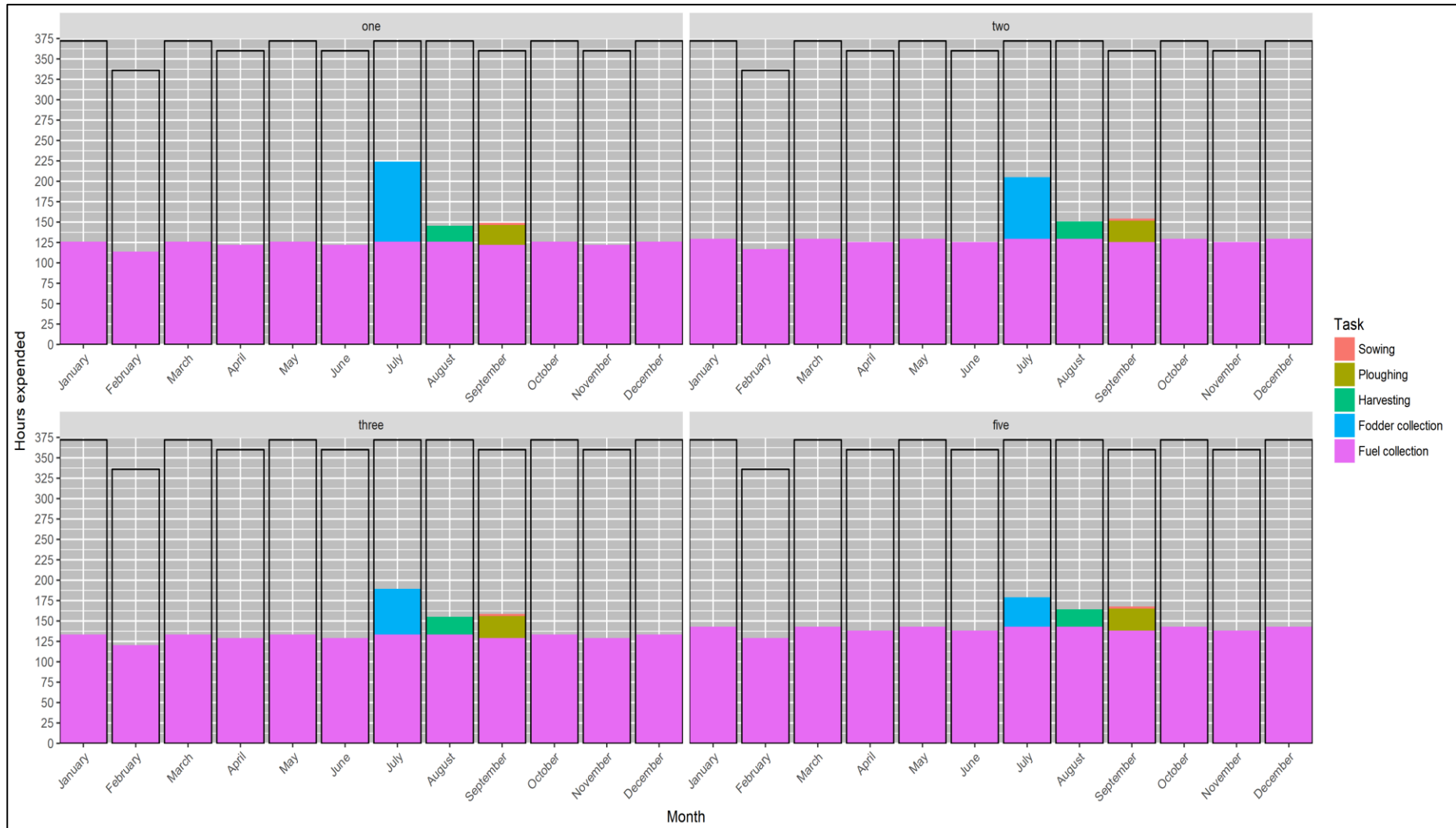


Figure 5.15. Monthly labour expenditure per member of “strong” workforce in settlements undertaking subsistence-based farming with different number of households (panels) per task (bars) and total potential working hours per month (black outline) (year >=50).

6. Surplus production

In the previous chapter, the results from initial experiments that simulated scenarios of subsistence-based agriculture in the Dutch *limes* region prior to Roman occupation were analysed. The discussion focused on the relative importance of land or woodland and labour as limiting factors in agricultural production and the collection of firewood. In this chapter, the results of simulating different strategies of surplus production within a randomly-generated landscape are discussed with a similar focus on the relative importance of limiting factors (objectives v-vii). These different scenarios are described in chapter 4 (experiments B I-II, see section 4.4). By doing so the following research topics are considered:

- a) Changes in land and labour costs for strategies of surplus arable production (intensification and extensification)
- b) Quantities of surplus produced under different strategies of surplus arable production
- c) Possibilities of surplus production of animal products
- d) The requirements of land and labour for horse breeding

The scenarios simulated serve to reflect the possible ways that rural settlements could have shifted from subsistence-based agriculture to surplus production and the costs and impacts of this shift.

6.1. Strategies of surplus arable production

Archaeobotanical assemblages in non-native settlements contained both native weed flora and a cereal spectrum typical of that cultivated by local farmers in the region (see chapter 2 section 2.6.3). The botanical evidence implies at least a partial supply of the Roman military settlements and *vici* by local farmers. Different assumptions have been made regarding the mechanism by which rural farmers could have produced a surplus of grain for the army in the region and the inhabitants of towns and *vici*. It can be inferred that in Kooistra (1996) and van Dinter *et al.* (2014), for example, an extensification strategy was assumed. Calculations in these studies take into account whether sufficient extra land was available for settlements to cultivate. Conversely, Groot (2008a) suggests that changes in the management of cattle herds at Tiel-Passewaaij may reflect changes in arable farming from subsistence-based to intensification (see chapter 2 section 2.6.4 for manure use in the Roman world and the Roman Netherlands). Both strategies are capable of producing a surplus of grain, but little discussion has been made regarding different costs for surplus production. It is expected that the limiting impact that different factors have on surplus arable production strategies would differ. Furthermore, whilst at least some supply of surplus grain to Roman military settlements, towns and *vici* in the Lower Rhine delta is now considered likely (see chapter 2 section 2.8), it is important to discuss whether a significant shift from subsistence-based to surplus arable production was necessary.

6.1.1. Surplus production under subsistence-based farming

Settlements undertaking a subsistence-based arable farming strategy do not aim to produce any extra grain than is required for consumption, sowing seed and a buffer (for the importance of the latter see chapter 5 section 5.2.2). Given that grain yields can fluctuate each year not only negatively but also above the average that settlements predict, settlements can inadvertently produce a further small surplus. The potential surplus that can be produced by settlements with different numbers of households is provided in figure 5.7. It has already been discussed in the previous chapter (section 5.2) that the surpluses produced by settlements differ according to the size of the settlement. The more households a settlement has, the larger area of land that settlements will cultivate to provide their inhabitants with sufficient grain to consume, sowing

seed and a buffer. In addition, settlements will cultivate larger areas of land as the proportion of the inhabitants' diet that is grain-derived increases. Hence in years when grain yield exceeds the average grain yield predicted by settlements, surpluses will be larger because more land is cultivated. Accordingly, the surplus produced is greatest under subsistence-based arable farming by settlements with five households with inhabitants deriving 100% of the required calories from crops.

Unlike surplus strategies in arable farming, the production of surplus grain under subsistence farming incurs no extra labour or land costs. However, surplus grain produced under subsistence-based farming is minimal. In addition, settlements are not guaranteed a surplus each year because the production of a surplus depends on grain yields randomly fluctuating above the average yield. This would be disadvantageous for rural settlements supplying military settlements towns and *vici*. If settlements were required to produce a surplus of grain through mechanisms of taxation or forced acquisition for example, settlements would be disadvantaged in those years where random fluctuations in grain yield were not positive. Similarly, military settlements and *vici* deriving part of the grain required from local producers would not be able to rely on an annual surplus being produced.

6.2. Alternative strategies of arable farming

Settlements in ROMFARMS can undertake either arable strategies of intensification or extensification. These strategies are but two possible strategies of agricultural change, however. It is worth here to repeat the definition of these two strategies both in terms of agricultural economics as well as how they are simulated in ROMFARMS. Ellis (1993, 206) distinguished between intensification and extensification as the relationship between land use and resource input. Therefore, extensification results in a large farm with small quantities of other resources inputted and intensification results in a small farm size with a large input of other resources. De Hingh (2000, 43) proposed two varieties of these strategies: extensification can either be an increase in the area of land used with the same input of labour or resources; intensification can be an increase in resources inputted and a decrease in the area of land. Bieleman (2010, 17) similarly noted that extensification was characterised by the use of a large area of land relative to labour or capital investment and intensification vice versa. It is important to highlight however that these terms are relative and do not have to involve "an absolute increase or expansion" (De Hingh 2000, 44). Accordingly, whilst an increase in the area cultivated would necessarily require an absolute increase in labour input, if the labour input per unit of land did not increase this could still be denoted extensification. Although Bieleman (2010) focused only on the investment of labour or capital within intensification, Ellis (1993) and De Hingh (2000) have noted that fertilizer or manure can also be considered a viable resource. Indeed, the economic value of manure within arable farming as a resource to increase grain yield suggests there is no need to exclude manure from a classical definition of agricultural capital.

In ROMFARMS, settlements can practice either intensification or extensification when surplus arable production is undertaken (see also chapter 4 sections 4.3.4). Under extensification settlements will use surplus grain, i.e. grain that exceeds the quantity required for consumption, sowing seed and a buffer, to sow more land. Although labour does increase in absolute terms, labour per hectare does not increase. Settlements undertaking intensification will not cultivate extra land but will incorporate manure into the same area of arable land that they would use for subsistence purposes. Per unit of land there is an increase input of labour (via the labour expenditure for manure incorporation) and an increase in the input of resources (manure). As with subsistence-based farming, the relative importance of limiting factors is discussed here to

highlight the restrictions that settlements experience when undertaking strategies of surplus arable production.

6.2.1. Arable extensification

Under extensification, the area of land cultivated is potentially the greatest among the three possible arable strategies (subsistence-based, extensification and intensification) that settlements can undertake. Although labour expenditure per hectare does not increase, the absolute labour expenditure would also be high. As with subsistence-based arable farming, settlements are limited by the availability of land, labour and sowing seed. Without extra sowing seed settlements are unable to cultivate extra land. Settlements also require access to larger areas of arable land and therefore labour to cultivate larger areas of land when extensification is pursued.

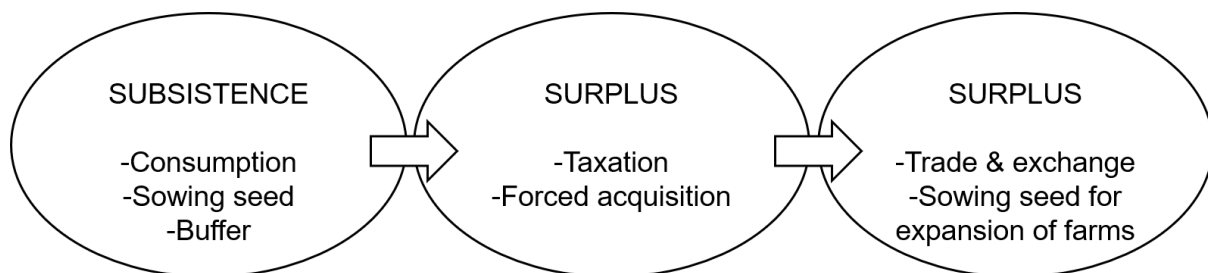


Figure 6.1. Hierarchy of grain uses for rural settlements in ROMFARMS.

6.2.1.1. The impact of limiting factors

6.2.1.1.1. Availability of sowing seed

Settlements undertaking extensification use surplus grain as extra sowing seed to cultivate larger areas of land than are required for the production of grain for their own consumption, sowing seed and a buffer. Surplus grain is defined in this study as any grain not required by the settlements for their own needs but that can be used to fulfil the needs of the military through taxation, forced acquisition or trade, or to expand settlements' own farms (see figure 6.1). Grain needed for subsistence purposes includes grain for a settlement's consumption, grain to sow enough land to grow enough grain for consumption needs and a "buffer". When settlements undertake extensification, surplus grain also includes grain that can be used to sow extra land especially as other uses, such as use for taxation purposes or its use in trade and exchange, are not simulated by ROMFARMS. Without surplus grain therefore, settlements are unable each year to cultivate extra land. This has consequences for the proportion of surplus grain that can be removed from settlements. In figure 6.2, the quantity of surplus available to consumer settlements from a single farming settlement is provided when different proportions of surplus grain are removed to be used to supply military settlements, towns and *vici*. When the proportion of surplus grain removed from settlements is nil, settlements can use all surplus grain each year to sow extra land. If all surplus grain is removed, the quantity of surplus each year does not differ from that produced under subsistence-based arable farming (see this chapter section 6.2.1). This is because there is no extra sowing seed available each year to sow extra arable land. The optimal proportion of surplus grain that is removed each year is c. 70%. The behavioural goals of settlements undertaking extensification are to expand farms to their greatest extent within the confines of labour availability as well as produce the largest amount of surplus for other consumers. The optimum proportion of surplus grain that can be removed is the proportion that doesn't restrict the labour force nor restricts the available surplus, therefore. If a larger proportion of surplus grain than 70% is removed, the area that can be sown with remaining

surplus grain begins to decrease as too little sowing seed remains. If a smaller proportion of surplus grain is removed, the quantity of surplus grain available for military settlements, towns

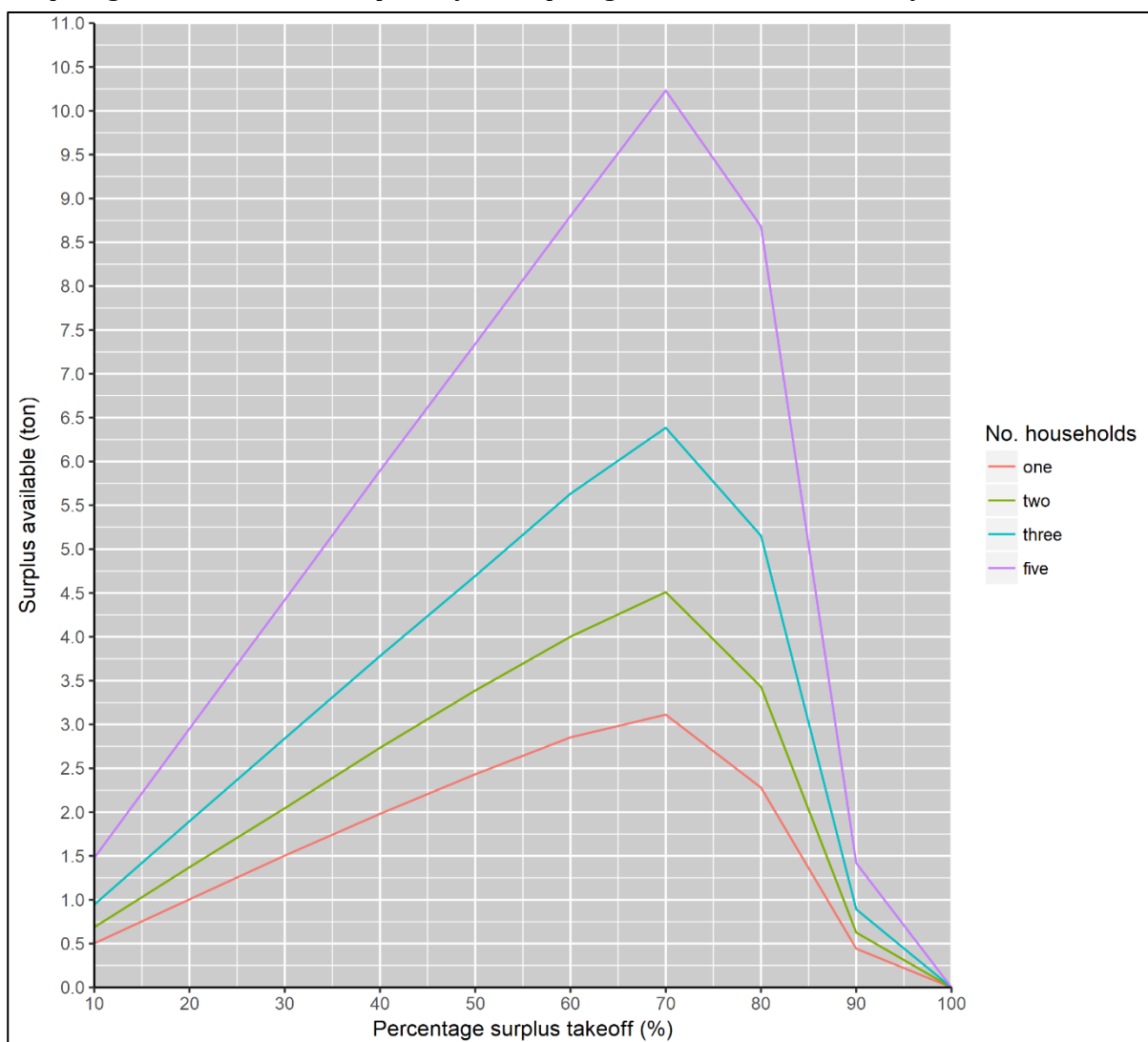


Figure 6.2. Annual surplus grain available to consumer-only settlements from each rural settlement of different sizes when 70% of the inhabitants' diet is grain-based and when different proportions of surplus grain are removed each year.

and *vici* is naturally smaller. Furthermore, the extra sowing seed can't be used beyond the restrictions that the available workforce place on farm expansion. In both these scenarios the behavioural goals of extensification are contravened.

The take-off or proportion of surplus grain that can be removed annually could be reflective of the possible limits of taxation or requisition that could have been imposed on settlements in the region. Requisition of all surplus produced by settlements in one year would severely restrict agricultural productivity in the next whereas requisition or taxation of less than 70% would not restrict surplus arable production in terms of sowing seed available. Of course, this provides no results related to the nature of any taxation or acquisition. The impact of different taxation mechanisms such as informal taxation in kind or a formal monetary taxation is not currently addressed in ROMFARMS.

6.2.1.1.2. Availability of labour

When settlements undertake extensification and 70% of the surplus produced is removed, the availability of labour is most limiting. The labour pools available to settlements limits the maximum area of extra arable land that can be cultivated, and this is lower than the area of land settlements can sow with the total surplus grain (see table 5.3, chapter 5 section 5.2.3). The results show that the area of land actually cultivated by settlements undertaking extensification is lower than the calculated maximum area that can be cultivated by the “strong” workforce. This means therefore that more surplus can be removed than shown in figure 6.2. Scenarios with different surplus take-offs were simulated using increments of 10% meaning that the actual optimum surplus take-off falls between 70 and 80%. The difference between the actual area of land to be cultivated and the predicted area of land based on labour availability is small although increases as the size of the settlement decreases (c.f. tables 5.2 & 6.1). This is as a result of the greater stochasticity in populations in scenarios with smaller settlements (see chapter 5 section 5.1). Consumption patterns have no impact on the area of land settlements cultivate each year when undertaking extensification. Settlements will seek to cultivate the maximum area that the availability of labour allows regardless of the proportion of the inhabitants’ diet is derived from grain.

STRATEGY	NO. HOUSEHOLDS	PROPORTION DIET GRAIN BASED (%)									
		0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
SUBSISTENCE	one	0.25	0.50	0.74	0.99	1.24	1.49	1.73	2.00	2.23	2.49
	two	0.34	0.68	1.02	1.36	1.71	2.05	2.39	2.73	3.07	3.40
	three	0.47	0.94	1.41	1.89	2.36	2.83	3.29	3.77	4.25	4.71
	five	0.73	1.46	2.19	2.92	3.65	4.38	5.07	5.87	6.57	7.30
INTENSIFICATION	one	0.25	0.49	0.74	0.99	1.24	1.49	1.73	1.98	2.22	2.47
	two	0.34	0.68	1.02	1.36	1.71	2.05	2.39	2.73	3.06	3.40
	three	0.47	0.94	1.41	1.88	2.35	2.82	3.30	3.77	4.23	4.69
	five	0.73	1.46	2.19	2.92	3.64	4.37	5.11	5.84	6.59	7.27
EXTENSIFICATION	one	4.99	5.37	5.48	5.62	5.74	5.81	5.88	5.92	5.86	5.99
	two	7.85	8.05	8.16	8.19	8.27	8.35	8.33	8.38	8.39	8.40
	three	11.4	11.5	11.6	11.8	11.7	11.8	11.7	11.7	11.7	11.8
	five	18.5	18.4	18.5	18.6	18.6	18.6	18.6	18.6	18.6	18.6
		7	7	5	9	8	3	4	0	4	3

Table 6.1. Area of arable land cultivated by settlements undertaking subsistence-based arable farming, intensification or extensification with different number of households to produce grain for consumption and sowing seed with different proportions of the diet grain-derived (year ≥50).

6.2.2. Arable intensification

Settlements undertaking intensification do not increase the area of land cultivated beyond that cultivated under subsistence-based arable farming. Rather, per unit of land settlements will increase the input of labour and resources. This takes the form of the application of manure to arable land which is not only a valuable albeit limited resource available to settlements from cattle herds but also requires the expenditure of extra labour. Intensification is limited by the same limiting factors as subsistence-based arable farming and arable extensification (the availability of sowing seed, labour and land) as well as the availability of manure.

6.2.2.1. The impact of limiting factors

6.2.2.1.1. Availability of sowing seed

Settlements are not limited as significantly by the availability of sowing seed as under subsistence-based arable farming. Given that settlements do not cultivate extra arable land under intensification and that settlements are already able to produce sufficient sowing seed for the required area of arable land (see chapter 5 section 5.2.3.3), any surplus grain is superfluous as sowing seed. Settlements possess more sowing seed than is necessary each year therefore (see table 5.2). Given that settlements do not require the surplus grain produced each year for sowing seed, there is no limit to the amount of surplus grain that can be removed from the settlement before the availability of surplus sowing seed begins to have a limiting impact on arable productivity. Thus, all surplus grain produced is available for supply to settlements not producing their own food e.g. military settlements or *vici*. Again, this has implications on possible taxation or requisition strategies, as, unlike under extensification (see section 6.2.1), there is no negative impact if all surplus grain produced is removed from settlements.

6.2.2.1.2. Availability of manure

Settlements undertaking intensification rely on the positive effects on yield that the application of manure on arable land provide (see chapter 4 section 4.3.4). In addition, the application of manure negates the requirement to leave cultivated arable land fallow in the following year. Given that settlements do not increase the area of arable land cultivated, if settlements do not possess manure then no extra grain can be cultivated. Furthermore, if the quantity of manure settlements possess each year is less than the optimum (10t per hectare; see section 4.3.4 chapter 4), the quantity of surplus grain cultivated would be reduced as the quantity of manure per hectare is reduced. The quantity of surplus grain produced is therefore limited by the availability of manure with the availability of manure determined itself by the exploitation strategy of cattle undertaken by settlements. Settlements must therefore keep cattle herds to undertake intensification.

The quantity of manure required by settlements applying the optimum to arable land is provided in figure 6.3. In addition, the average yield of manure from a single modelled cattle herd under different exploitation strategies is provided. The results show that for smaller settlements with one or two households, settlements with three households deriving less than 70% of their diet from grain or settlements with five households deriving less than 50% of the diet from grain, a single modelled cattle herd exploited for manure can provide sufficient manure to apply 10t per hectare of arable land used, regardless of exploitation strategy (see chapter 5 section 5.3.1.3 for discussion regarding herd sizes and multiple herds). Owing to reduced manure yields from cattle exploited for manure, settlements with three or five households deriving a larger proportion of the diet from grain require at the same number of animals as in two modelled cattle herds to produce sufficient manure. The manure yields from cattle exploited for milk is sufficient for all settlements deriving up to 100% of the diet from grain and settlements exploiting cattle for meat will not require more animals than in one simulated herd unless more than 90% of the inhabitants' diet is grain-based.

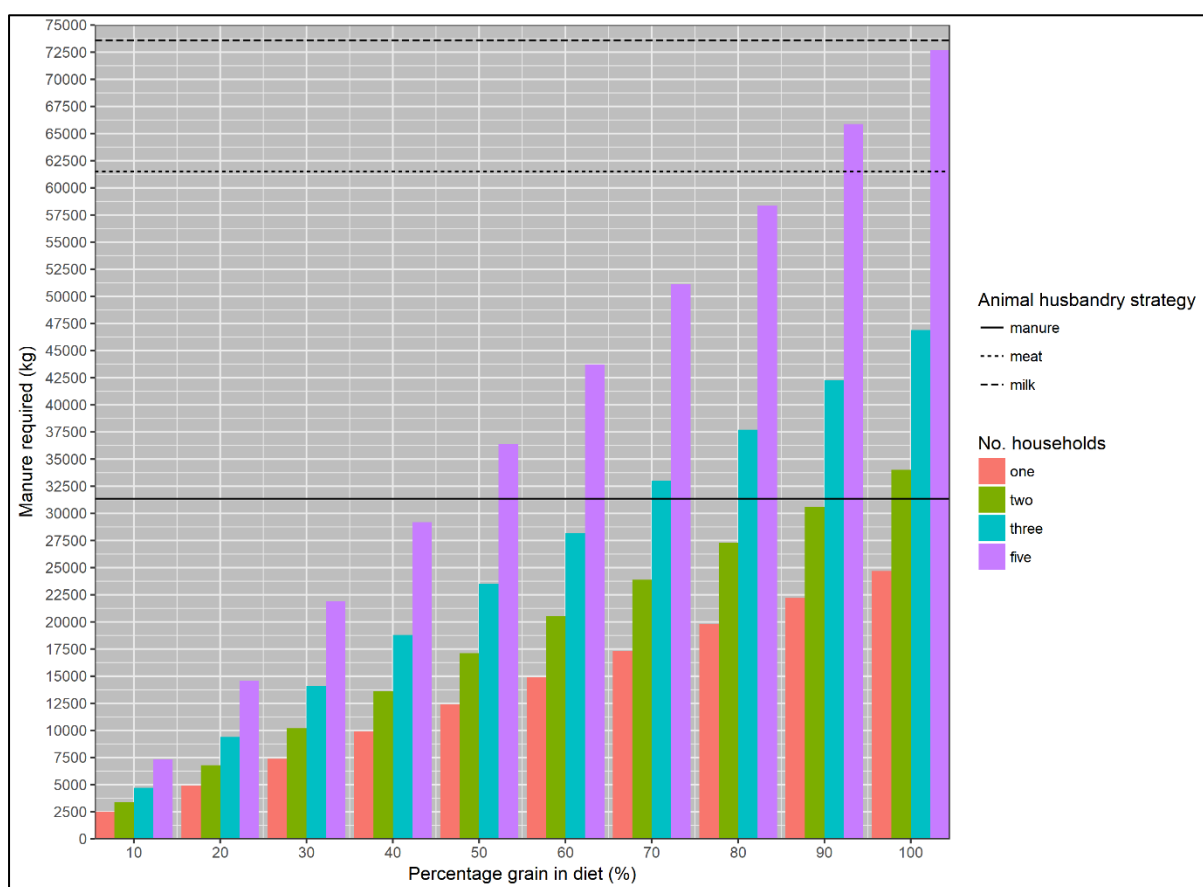


Figure 6.3. Total quantity of manure required by settlements undertaking intensification and with different proportions of grain in diet (bar) and total area of land that can have optimal manure application (10t/ha) with manure yield from a single modelled cattle herd under different exploitation strategies (lines).

6.2.2.1.3. Availability of labour

Under intensification, settlements do not cultivate extra arable land and therefore settlements are only as limited by the availability of labour as settlements undertaking subsistence-based farming (see chapter 5 section 5.2.3.2). However, labour expenditure per hectare is increased as settlements must invest labour in the application of manure to arable land. Furthermore, manure is essential to increase yields under intensification and therefore the labour required must include the labour for the collection of fodder for cattle. As has been discussed previously (see chapter 5 section 5.3.2), settlements are not restricted by available labour to keeping just one herd of cattle. The total number of animals that can be kept is more than the total needed to produce enough manure for optimum application in the area of land that settlements cultivate. Settlements are not significantly limited by the availability of labour when practicing intensification, therefore.

6.2.3. Summary: the strategies compared

The two strategies of surplus production thus differ in relation to the relative importance of limiting factors that affect settlements' ability to produce surplus grain each year. Settlements in a randomly-generated landscape undertaking extensification are more limited by the availability of labour. Under this strategy, the labour pool available to settlements is not large enough to cultivate as much land as can be sown with available surplus sowing seed. Settlements

undertaking intensification are limited more significantly by the availability of manure. In addition to the relative impact of limiting factors differing, both the land and labour costs as well as the quantity of surplus grain produced each year differ.

6.2.3.1. Surplus grain produced

The potential quantity of surplus grain produced each year by settlements undertaking an extensification and intensification compared with the surplus grain produced under subsistence-based arable farming is provided in figure 5.7. Under both surplus production strategies, the quantity of surplus grain produced is significantly higher than surplus grain produced by settlements practicing subsistence-based arable farming. Comparisons of surplus grain produced under extensification and intensification also show that extensification produces more surplus grain than intensification.

An alternative mechanism for comparing the two strategies of surplus grain production and the subsistence strategy is to analyse the cost effectiveness of each strategy in producing surplus grain by comparing the total extra investment of arable land or labour per unit (ton) of surplus grain produced. Table 6.2 shows the extra area and hours necessary per ton of surplus grain produced under strategies of intensification and extensification. For extensification these extra costs, as discussed above, are only the extra land cultivated and the labour required to cultivate this extra land. For intensification, these calculations take into account not only the labour required for sowing, ploughing and harvesting but also for the application of manure. In addition, because manure is essential to produce surplus grain, the labour required to collect fodder for cattle herds is considered an additional expenditure of intensification. As settlement size increase, the number of cattle needed to produce the necessary manure increases as does the surplus grain produced. This means that the extra hours per ton settlements need to invest to produce surplus grain under intensification fluctuates.

STRATEGY	NO. HOUSEHOLDS	HECTARES PER TON	HOURS PER TON
EXTENSIFICATION	one	1.34	75.64
	two	1.34	74.86
	three	1.34	74.30
	five	1.35	73.91
INTENSIFICATION	one	0	131.01
	two	0	120.05
	three	0	133.24
	five	0	126.64

Table 6.2. The extra area of land and hours needed to produce 1 ton of surplus grain under intensification and extensification.

Cost-benefit analysis indicates that, depending on the availability of land and labour, one of the strategies is more advantageous than the other. This differs from analysis based on absolute surplus grain produced which would suggest arable extensification is always more advantageous. The reduced land cost per unit of surplus grain means that intensification is the optimum strategy when settlements have limited access to new arable land. Conversely, the labour costs per ton of surplus grain are lower under extensification despite total costs being higher for the arable tasks. Accordingly, extensification may be more cost effective for settlements with limited availability to labour, whether that be owing to incomplete households or the size of the settlement.

6.2.3.2. Changes to the agricultural calendar

An analysis of monthly labour expenditure for all agricultural tasks was provided for subsistence-based agriculture (see chapter 5 section 5.5.1). The results showed that settlements with an

average-sized labour pool do not encounter bottlenecks during the year, however settlements with only one household would be affected by incomplete households i.e. only one adult living in the settlement. Given that both strategies of surplus arable farming require higher labour costs, a similar analysis was conducted to investigate whether any further labour bottlenecks would be experienced by settlements pursuing a strategy of surplus grain production.

The monthly labour costs by settlements of different sizes for arable tasks and fuel collection are provided in figures 6.4 & 6.5. If settlements have a labour pool of average size no bottlenecks occur under extensification, although the amount of surplus potential labour available in months where arable tasks are completed (August and September) is significantly reduced. However, single household settlements with an incomplete household will experience a potential bottleneck when arable land is prepared for cultivation in September (see figure 6.6). The total number of hours expended by the limited workforce of one adult in an incomplete household on ploughing and sowing of arable land exceed the potential number of hours within the month. Small settlements with one household undertaking intensification experience no such bottlenecks if cattle are exploited for manure. However single household settlements exploiting cattle for either meat or milk will experience a labour bottleneck when there is an incomplete household with just one adult male or female (see figure 6.7).

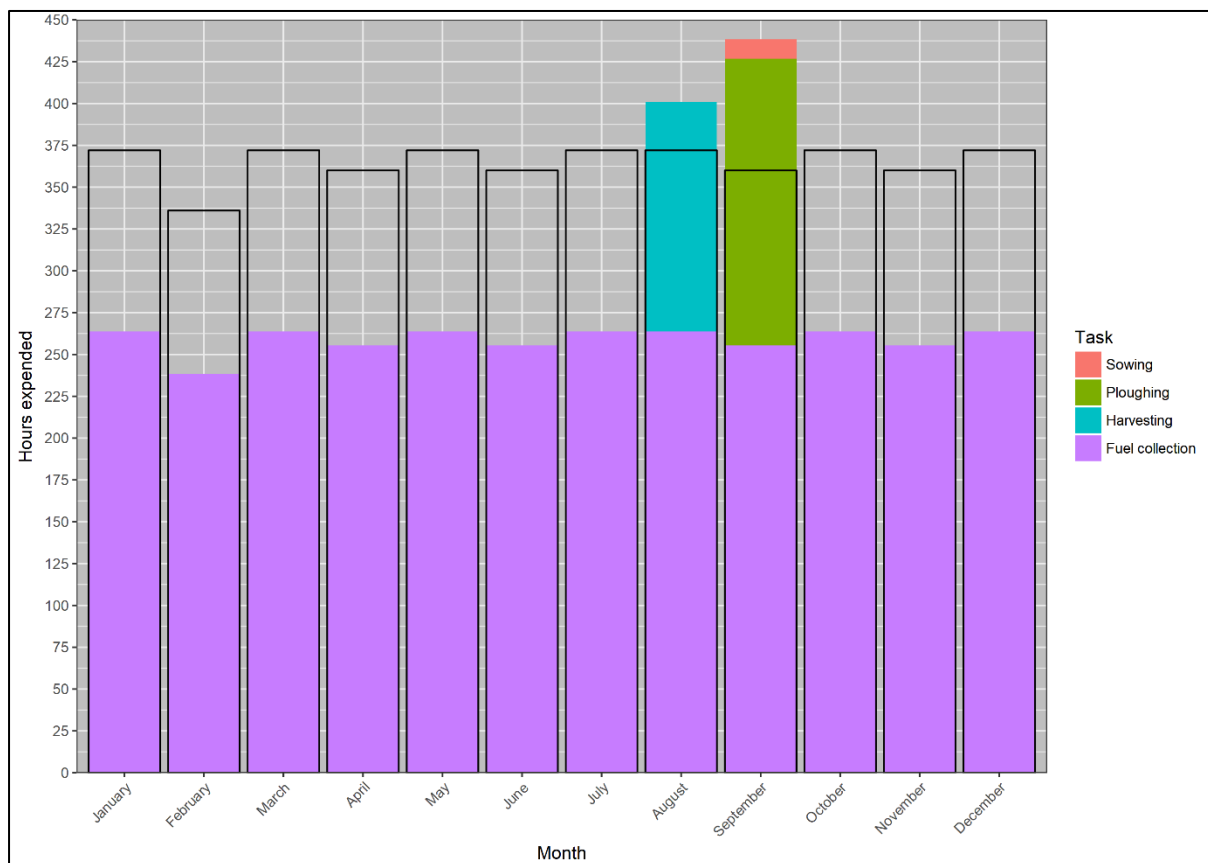


Figure 6.6. Monthly labour expenditure for settlements with one household with one member of "strong" workforce undertaking extensification and total hours per month (black outline) (year >=50).

The impact of incomplete households (households where a married adult female or male is missing) was highlighted by van Dinter *et al.* (2014) as a possible limiting factor within the agricultural economy of the Dutch *limes* zone. The risk of incomplete households came not only from high mortality rates but also because of the significant level of recruitment that the local population experienced during the Roman period. For larger settlements, an incomplete

household does not pose a significant reduction in labour as there are multiple households. For settlements comprising single households however an incomplete household can result in a settlement having only a single member of the “strong” workforce available. The likelihood of this occurring due to natural mortality is low but was perhaps more prevalent due to recruitment. The results confirm the assumption made previously that small settlements in the Dutch *limes* zone would have encountered significant restrictions owing to incomplete households. Single household settlements with an incomplete household are unable to complete some agricultural tasks within the allotted time. It can be expected that in cases where small settlements have an incomplete household the results show that they needed to mitigate this labour deficit. Although in ROMFARMS there is no provision for exploring different ways that this could be achieved by settlements, labour sharing or utilising casual hired labour could have been mitigating strategies.

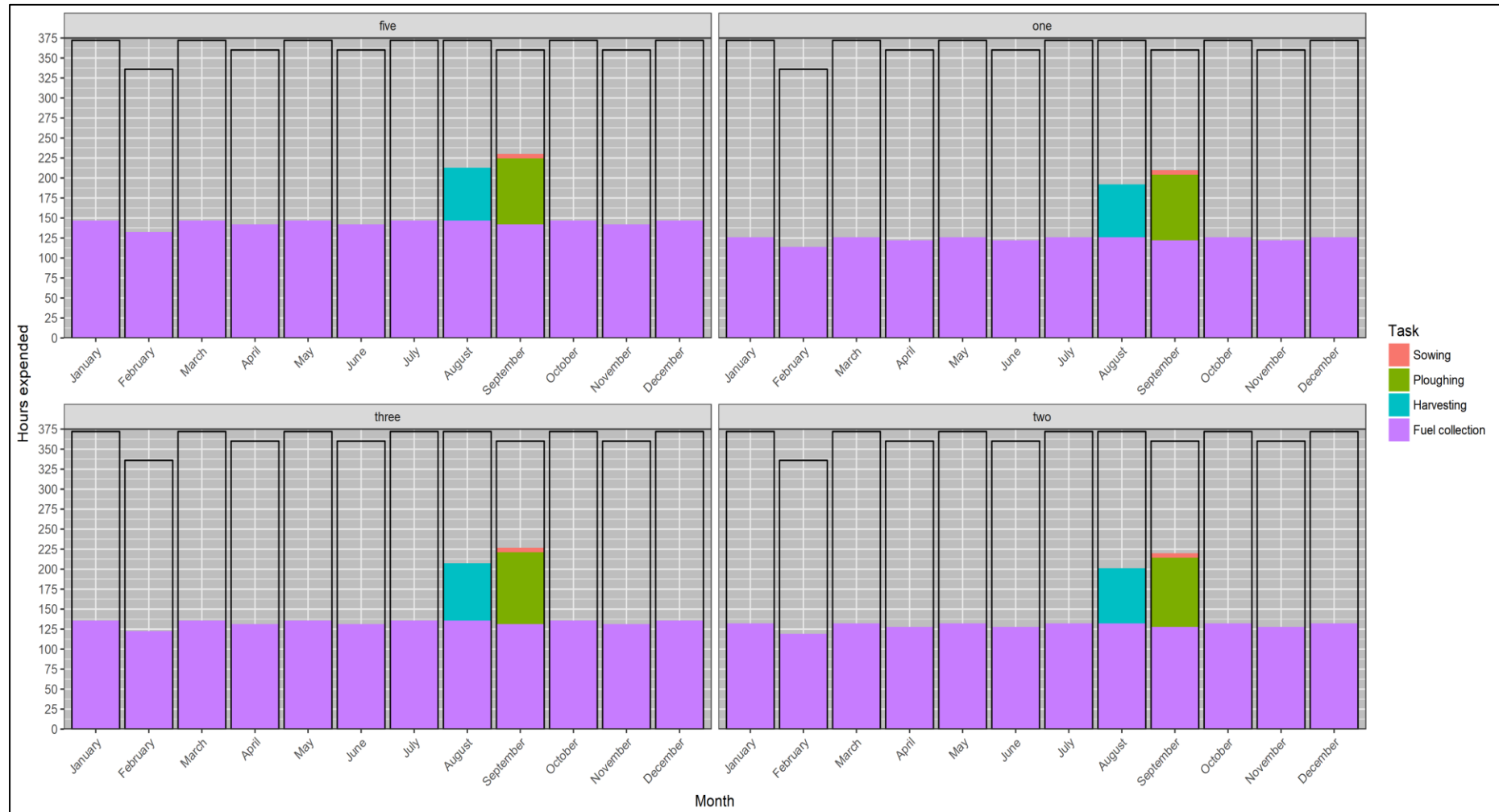


Figure 6.4. Monthly labour expenditure per member of "strong" workforce in settlements undertaking extensification with different number of households (panels) per task (bars) and total potential working hours per month (black outline) (year ≥ 50). NB fodder collection has not been included as animal husbandry is not a prerequisite for arable extensification.

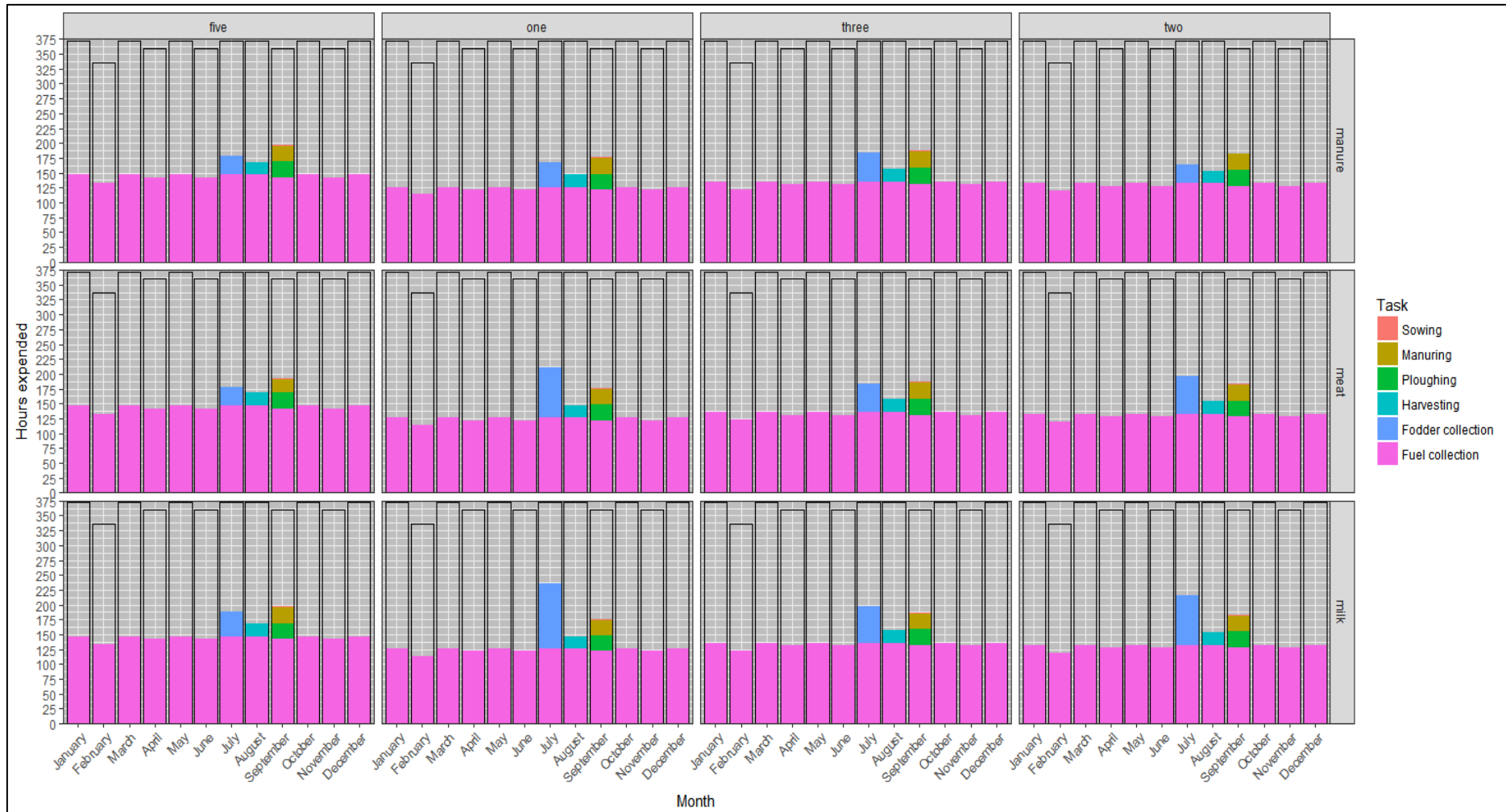


Figure 6.5. Monthly labour expenditure per member of "strong" workforce in settlements undertaking intensification and different animal husbandry strategies with different number of households (panels) per task (bars) and total potential working hours per month (black outline) (year >=50).

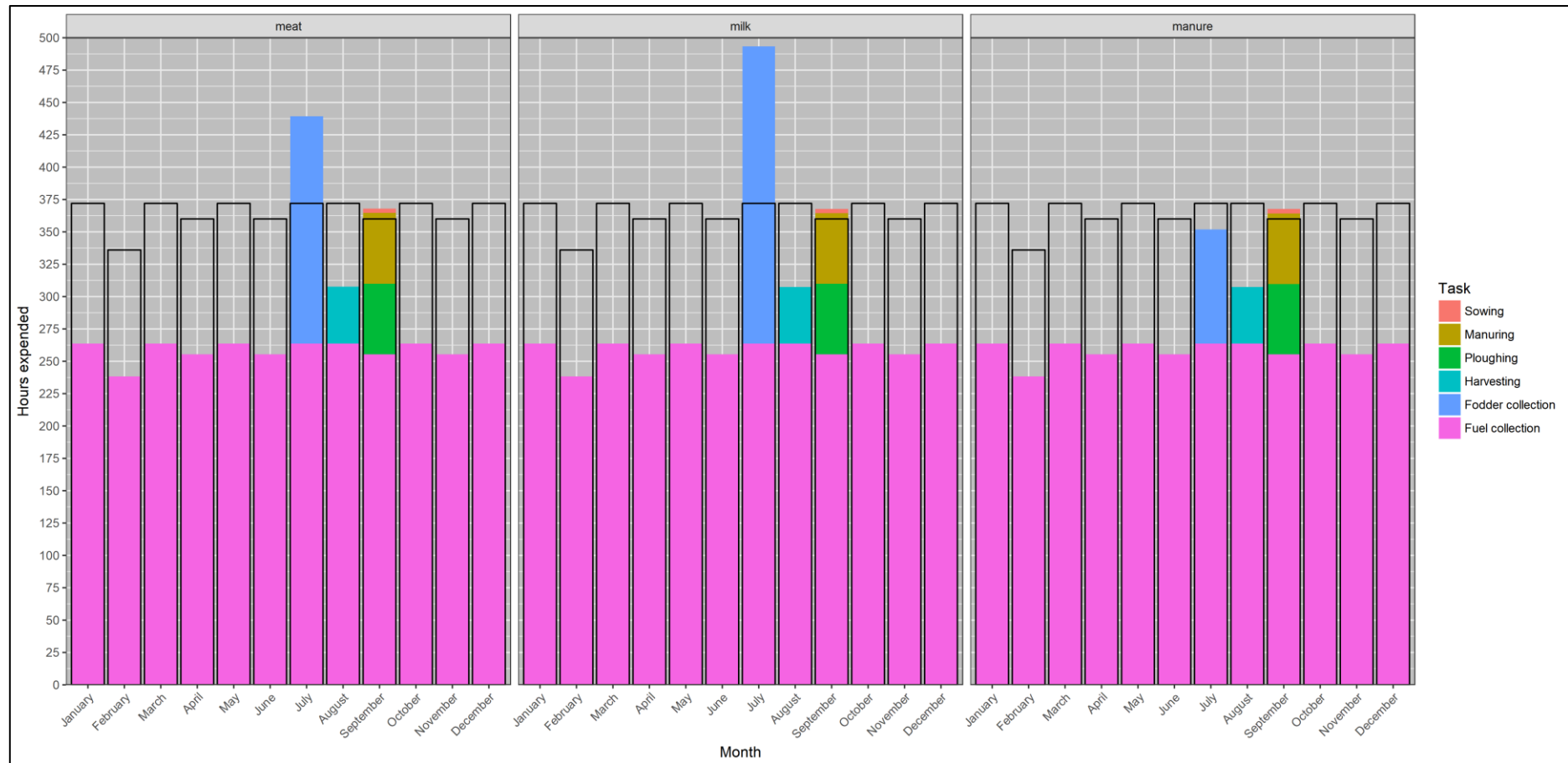


Figure 6.7. Monthly labour expenditure for settlements with one household with one member of “strong” workforce undertaking intensification and different animal husbandry strategies and total hours per month (black outline) (year >=50).

6.2.3.3. A third way? Combining intensification and extensification

Although only two strategies of surplus arable farming are simulated in ROMFARMS, these strategies are modelled as either-or whereby settlements can either undertake intensification or extensification as a mechanism of surplus arable production. It is worth considering however the feasibility for settlements to undertake a combined strategy utilising the yield boosting effects of applying manure to arable land and cultivating more land than would be under subsistence or intensification strategies. Settlements undertaking a combined strategy would be limited by both the availability of labour as under extensification which restricts settlements to cultivating an upper limit of land, and by the availability of manure as under intensification which is limiting in scenarios when manure available to settlements is less than the optimum application rate.

The quantity of manure required under a combined surplus arable farming strategy would be significantly greater than under an intensification strategy because settlements would cultivate greater areas of arable land as under an extensification strategy. The manure yield from cattle herds under different exploitation strategies have been presented in the previous chapter (see section 5.3.1.2) and discussed in relation to the manure required by settlements undertaking a strategy of intensification (see section 6.2.2.1. this chapter). When settlements exploit cattle for manure, the smaller herd size requires settlements with three or five households to keep more cattle than in a single-household settlement as simulated in ROMFARMS to have access to sufficient manure for optimal application (see chapter 5 section 5.3.1.1 for the size of cattle herds under different exploitation strategies). For settlements undertaking a combined strategy, the manure yield from a single cattle herd exploited for manure would be insufficient for all settlement sizes to undertake an optimal manure application on the arable land to be cultivated. Settlements undertaking combined strategy and exploiting cattle for manure would need between two and six times the manure produce by a single herd. Furthermore, the manure yields from a single cattle herd under the conditions imposed by all exploitation strategies are insufficient for all but two scenarios (these scenarios being settlements with one household exploiting cattle for meat or milk).

There is no provision in ROMFARMS for the simulation of a combined strategy incorporating behaviour from both intensification and extensification. However, the results from simulating the strategies separately permits some preliminary speculation regarding the feasibility for settlements to undertake a combined strategy of surplus arable farming. The area of extra land that would be cultivated under a combined strategy (as under extensification) is limited by the availability of labour and the availability of manure further limits surplus grain produced (as under intensification). The increased area of land that would be cultivated requires more manure than a single herd of cattle can produce regardless of exploitation strategy. Settlements would need to keep between the equivalent numbers of cattle as in one or two herds exploited for meat or milk as simulated to have access to sufficient manure, and even more animals when herds are exploited for manure. This is feasible as far as labour limits settlements, and thus, a combined strategy of the two simulated strategies of extensification and intensification can be undertaken by settlements. The availability of sufficient access to pasture and meadow land would restrict the feasibility that a combined strategy could be undertaken in the Dutch *limes* landscape, however.

6.3. Surplus production of animal products

As discussed in the previous chapter (see section 5.3), whether settlements can produce a surplus of animal products is based on calculations using the results from simulations of individual herds of sheep and cattle. The starting assumption is that each settlement kept one of the modelled herds of cattle or sheep (or both). If one herd can produce more animal products than required

by a settlement, a surplus of animal products is produced. Further calculations are based on settlements keeping multiple herds identical to herds simulated in ROMFARMS. Therefore, when the yields of different products from a single modelled herd of animals is not sufficient to produce a surplus, more animals are needed. Calculations of yields from extra animals are based on the equivalent yields from two or more simulated herds. It is more realistic that settlements would keep larger herds rather than multiple herds but that requires simulating animal herds with different parameter values than already developed by ROMFARMS.

In addition to the surplus production of grain, zooarchaeological evidence points to a possible local supply of surplus animals or animal products. Although van Dinter *et al.* (2014, 30) argued that the size of herds necessary to supply inhabitants of military settlements and *vici* would have required too many animals for a settlement to manage, it was discussed previously that settlements in ROMFARMS are not always restricted by the availability of labour in keeping the equivalent number of cattle that are in one simulated herd (see chapter 5 section 5.3.1.1). If settlements derive 30% or less of the total calories required from animal products, they can already produce a small surplus of animal products from a single herd when exploiting cattle for meat or milk (20% or less for cattle exploited for manure). As the size of the settlement increases or as the proportion of the diet that is animal-based increases, this potential surplus of animal products declines and in some scenarios a deficit of animal products is experienced by settlements. Settlements with multiple (two or more) households have sufficient available labour to collect fodder for more animals when exploited for meat and milk, and all settlements can collect sufficient fodder for more animals when cattle are exploited for manure. If settlements derive a greater proportion of the diet from grain than animal products, a small surplus of animal products would be available from the number of cattle in a single modelled herd of cattle exploited for meat or milk. Larger settlements would be, as far as labour is a limiting factor, able to produce yet larger surpluses by keeping even more animals.

It was previously discussed also that the quantity of meat or milk supplied by sheep herds was significantly smaller than that supplied by cattle herds (see section 5.3.1.2 chapter 5). It was argued that even in scenarios where settlements derive relatively few calories from animal products, even settlements with a single household would unrealistically need to keep very many sheep. Zooarchaeological assemblages from rural settlements in the Dutch *limes* zone indicate that sheep were not as important in the rural agricultural economy as cattle. Furthermore, van Dijk & Groot (2013) noted the decline in importance of sheep during the Middle Roman period. Widespread and significant surplus production of sheep for meat and milk would result in a relative importance of sheep within faunal assemblages not observed within the zooarchaeological record, therefore. Rather, if the maintenance of sheep herds played any part within surplus production in the region, small-scale surplus production of wool is more likely and better reflects archaeological data available (see Groot 2008a; van Dijk & Groot 2013).

Although previous studies concerning surplus production of animal products have largely focused on the supply of meat from rural settlements to the military settlements and the *vici*, the possible yield of milk from cattle herds regardless of exploitation strategy undertaken exceeds the output of meat. Therefore, the possibility of milk production as a method of surplus production among rural settlements should also be considered. The transportation of raw milk from rural settlements to military settlements or *vici* is unlikely given how quickly it can spoil, however the production of secondary dairy products such a cheese or butter for transport is a possibility. Although it is sheep or goat milk that the ancient sources say that cheese was made from (see Groot 2008a, 38), the production of cheese from cattle cannot be ruled out by its absence in ancient sources focusing on the Mediterranean area alone. Cheese production has been considered previously, albeit briefly, as a small-scale and specialised way of market participation

in the Roman period (van Driel-Murray 2003; 2008). The surplus production of milk or secondary dairy products is therefore a possible mechanism in which rural settlements in the Dutch *limes* region may have produced a surplus of food for military settlements and *vici*.

6.3.1. Horse breeding

As discussed earlier, the management of horses differs from sheep and cattle husbandry in ROMFARMS in so far as different strategies of exploitation are not undertaken (see chapter 4 section 4.3.5). Zooarchaeological evidence from the region points to little or no consumption of horse meat (Lauwerier 1988, 1999; Lauwerier & Robeerst 2001), with the most likely commodity being the horses themselves for use in the military or for transport purposes. In ROMFARMS therefore, horses are exploited in order to maximise the number of surplus immature horses that can be removed from the herd without causing the extinction of the herd.

6.3.1.1. Population size and composition

Natural mortality rates coupled with the removal rate of immature horses as a surplus commodity, results in a herd size and composition provided in tables 5.4 & 5.5. As with cattle and sheep herds, the majority of a horse herd simulated in ROMFARMS is comprised of adult animals. Young animals are in excess of immature animals. Given that immature animals are specifically targeted to be removed from the herd as a surplus commodity, this herd composition is not unexpected. The total number of heads per horse herd stabilises at c. 51 animals at which point the herd becomes stationary i.e. population growth is approximately 0%.

6.3.1.2. Land and labour costs

The total area of land and labour costs required by a single simulated horse herd is provided in table 5.7. The results show that, owing to the assumptions used in ROMFARMS, the areas of meadow and pasture land needed are relatively high. The areas required correspond most closely with cattle herds exploited for meat owing to similarities in herd composition and size. A single horse herd as modelled will require in total c. 25ha of land which corresponds to c. 11ha of meadow land and c. 14 ha of pasture land. The relatively high area of meadow land required to produce fodder for horse herds reflects also the relatively large labour expenditure to collect sufficient fodder. Each year in total, settlements must spend c. 171 hours in fodder collection for a single horse herd.

6.3.1.3. Availability of surplus horse

To prevent extinction of horse herds, settlements can only remove a limited number of immature animals each year as surplus. Removal of too many immature animals prevents enough animals reaching adulthood and producing offspring. Each year per modelled herd of c. 51 heads, an average of seven immature animals are surplus and can be removed from the herd as a commodity. The possibility of rural settlements undertaking surplus production not of grain, but horses has been an important part of the discussion related to agricultural productivity in the Dutch *limes* zone during the Roman occupation. Kooistra (1996) argued that horse-breeding could fulfil an obligation of surplus agricultural production in the region. Furthermore, Groot (2008b), Nicolay (2008) and Vossen & Groot (2009) have all proposed the possibility of specialised or intensive horse breeding owing to the ubiquity of horse bones in rural settlements, with some settlements containing between 20% and 30% horse bone within faunal assemblages by the Middle Roman period (see also Lauwerier & Robeerst 2001, table 1 for a partial inventory of military and rural sites with >100 faunal remains). Vossen & Groot (2009) calculated a yearly demand of 373 horse for the early Middle Roman period and 413 for the later Middle Roman period from the Roman army present in the *civitas Batavorum* area of the Dutch *limes* zone. This

calculation was based on a three-year service per horse and the number of forts located in the region (see Hyland 1990 for the use of horses in the Roman army). The actual number of horses required each year to replace horses that had died or were no longer in service would be greater for the whole region (taking into account the forts east of the *civitas Batavorum*). However, it is probable that with seven surplus horses bred each year by settlements, the estimated requirement from the studies above of the Roman army in the Dutch *limes* region could be fulfilled by local settlements. Furthermore, the results show that it was not necessary for every settlement in the region to undertake intensive horse-breeding. It is unrealistic that each settlement could have managed a herd of horses the size of herds modelled in ROMFARMS. However, the ubiquity of horse bones in the zooarchaeological assemblages suggests most settlements engaged in some form of horse breeding. Differences in the percentage of horse bone in assemblages in the region suggests a difference between specialised or intensive horse breeders whose large horse herds similar to those simulated in ROMFARMS produced sufficient surplus horses for the army and settlements undertaking horse breeding on a much smaller-scale.

6.4. Summary: possibilities for surplus production

A number of different strategies of surplus production have been suggested to have been undertaken by settlements in the Dutch *limes* research by previous research. Van Dinter *et al.* (2014) focused on the possibilities for extensification whereby settlements expanded the size of arable farms to produce greater quantities of grain. Furthermore, the possibilities of expansive animal husbandry were considered whereby settlements keep larger herds of cattle. Changes from the exploitation of cattle for milk or meat to the exploitation of cattle for manure and traction were indicative of intensification in some settlements (Groot 2008b; 2016). The ubiquity of horse bones in faunal assemblages from rural settlements was proposed as evidence of surplus production of horses, not to be consumed, but to be used by the military or transport purposes (Vossen & Groot 2009; Kooistra 1996). The limitations imposed by the landscape of the Dutch *limes* region were discussed in detail regarding extensification and animal husbandry in van Dinter *et al.* (2014) and also in Kooistra (2016). However, discussions of other forms of surplus production have largely been discussed in generalist terms without explicit analysis of the possible limitations from both the availability of land and labour. The discussion above provides an analysis of different possible ways that settlements in the Dutch *limes* zone could have produced a surplus of grain, animal products or horses for military settlements and *vici* during the Roman occupation.

By comparing the quantity of grain with the land and labour costs for extensification and intensification, it was shown that the increased absolute labour investment from extensification resulted in a better pay-off of surplus grain than intensification. However, intensification resulted in a more cost-effective way of using smaller areas of arable land. In addition, for both strategies of surplus production the relative importance of different limiting factors was gauged. For extensification, provided that the proportion of surplus grain removed is approximately 70% or less, settlements would have enough surplus sowing seed to sow more land than the adult inhabitants within settlements can cultivate. This, it was argued, has repercussions regarding possible mechanisms of taxation or requisition in the Dutch *limes* region. There exists an optimum proportion of grain that can be removed from the settlement. This maximises the quantity that can be supplied to settlements not producing their own food and ensures that rural settlements have sufficient surplus sowing seed each year to pursue an extensification. Settlements undertaking intensification are most significantly limited by the availability of manure without which surplus grain produced each year would be minimal. These conclusions are, however, based on the results of experimenting with different arable strategies within a randomly-generated landscape. Owing to these landscapes being unrealistic, it is not possible to assess the

limitations that land availability plays in agricultural strategies of the region, which is discussed in the following chapter.

The possibility of surplus production of animal products was also analysed. The results showed that smaller settlements with one or two households were already able to produce a small surplus of meat or milk when keeping just one cattle herd when exploited for meat and milk. Larger settlements would need to keep more cattle before surpluses of animal products would be available. Despite van Dinter *et al.*'s (2014) suggestion that labour restrictions would probably prevent surplus production of animal products, the results suggest otherwise. The collection of fodder for large numbers of animals is possible for the labour pool available to settlements in ROMFARMS. It was suggested also that the yields of meat and milk from sheep herds is so low that very many animals would be necessary before a surplus was available. Given that large numbers of sheep are not reflected in zooarchaeological assemblages from rural settlements in the Dutch *limes* zone, significant surplus production of meat and milk from sheep herds was unlikely. Rather, if sheep were indeed part of a surplus producing economy, wool would have been a more important product.

An analysis of the herd dynamics of horse herds showed that seven immature animals could be removed from the modelled herd each year as a surplus commodity from a herd of c. 51 animals. However, the costs for keeping a horse herd were high. With a surplus of seven horses per herd, it was argued that not all settlements would need to be specialised horse-breeders to fulfil the annual requirements of the Roman army in the region for horses. However, zooarchaeological assemblages from the region show horse to be very common in rural sites. Therefore, it was argued that whilst most settlements kept horses, only specialist or intensive horse-breeders would have kept horse herds large enough (as simulated in ROMFARMS) to produce a regular surplus of animals for military settlements in the Dutch *limes* region.

The results all show that the various ways that settlements could have produced a surplus of grain, animal products or horses were possible for small settlements with single households to large settlements containing five households. The land and labour costs for these strategies differed however indicating that different strategies were optimal for different settlements depending on the availability of land and labour. It can be expected therefore that surplus production in the *limes* zone was not homogeneous with variations among settlements throughout the whole region. In the following chapter, production by rural settlements of surplus grain and animal products are compared with the demands from military settlements and *vici* in a diachronic analysis to gauge the extent of local supply in the Dutch Roman *limes* zone. In addition, agricultural strategies are simulated in reconstructed landscapes to provide more realistic assessments of land availability as a limiting factor in different parts of the Dutch *limes* zone.

7. Possibilities and limitations in reconstructed landscapes

In the previous two chapters of discussion (chapters 5 & 6), the results of experimenting with different scenarios in randomly generated landscapes were analysed in order to gain a better understanding of how both subsistence-based agriculture and surplus agricultural production could have been affected by a variety of possible limiting factors. It was noted however that owing to the use of randomly-generated landscapes within these initial experiments, it was not feasible to assess the availability of land as a limiting factor in both arable farming and animal husbandry. The use of randomly-generated landscapes precluded the incorporation of realistic restrictions on the areas of arable, pastoral and meadow land available to settlements. In this chapter, the results of experiments simulated again in landscapes generated using GIS data of palaeogeographic reconstructions of the Dutch *limes* zone are discussed. By doing so, the following research objectives are tackled:

- To gauge the extent that the availability of arable, pastoral and meadow land restrict agricultural production in each of the sub-regions reconstructed (objective viii),
- To explore how the natural landscape in each sub-region could have shaped farming strategies (objective viii),
- To estimate the quantities of surplus grain or animal products that could have been produced in the sub-regions with settlements undertaking different strategies of surplus production (objective ix),
- To compare supply and demand in the sub-regions and what this can reveal about possible strategies or mechanisms that rural settlements supplied military settlements and *vici* in the Dutch *limes* zone (objective ix).

7.1. Description of sub-regions

7.1.1. Natural landscape: opportunities and challenges

A reconstruction of the landscape of the thirty-two sub-regions and their location within the Dutch *limes* zone discussion are provided in figure 7.1 and the proportion of land types that can be used for agricultural tasks in each sub-region is provided in figure 7.2. The reconstructions were completed by Groenhuijzen (2018; also Groenhuijzen & Verhagen 2015; 2016) using the methodology utilised by van Dinter (2013). This method refines geomorphological maps, pedological maps and channel belt data using local information and LIDAR elevation data (Groenhuijzen & Verhagen 2016, 28). Although this approach has enabled a palaeogeographical map of the study region with a scale of 1:50,000, uncertainties remain with the most likely landscape type being used for the reconstruction (*ibid.*). In addition to a brief description of the geographical context of the study region that was provided in chapter 2 (see section 2.4), a description of the sub-regions is provided here demonstrating the diversity of challenges and opportunities for rural settlements located within them.

In the western, coastal regions (regions 1 & 18) the coverage of levee and other higher elements of the landscape which settlements could have used both for arable farming and habitation were limited. However, the dunes and beach ridges found in these coastal sub-regions could have been used for arable farming (Kooistra *et al.* 2013). Settlements could have taken advantage of salt marshes located on tidal flats for grazing of animals in addition to any areas of floodplain where grassland was available for both pasture and the production of winter fodder for animals. Sub-regions further inland in this western region (regions 2-4 and 21-26) are characterised by only narrow corridors of levees with greater areas of floodplains (significantly greater in the more southerly sub-regions). Settlements would therefore be challenged by the limited availability of suitable land for habitation. On either side of these narrow corridors, broad

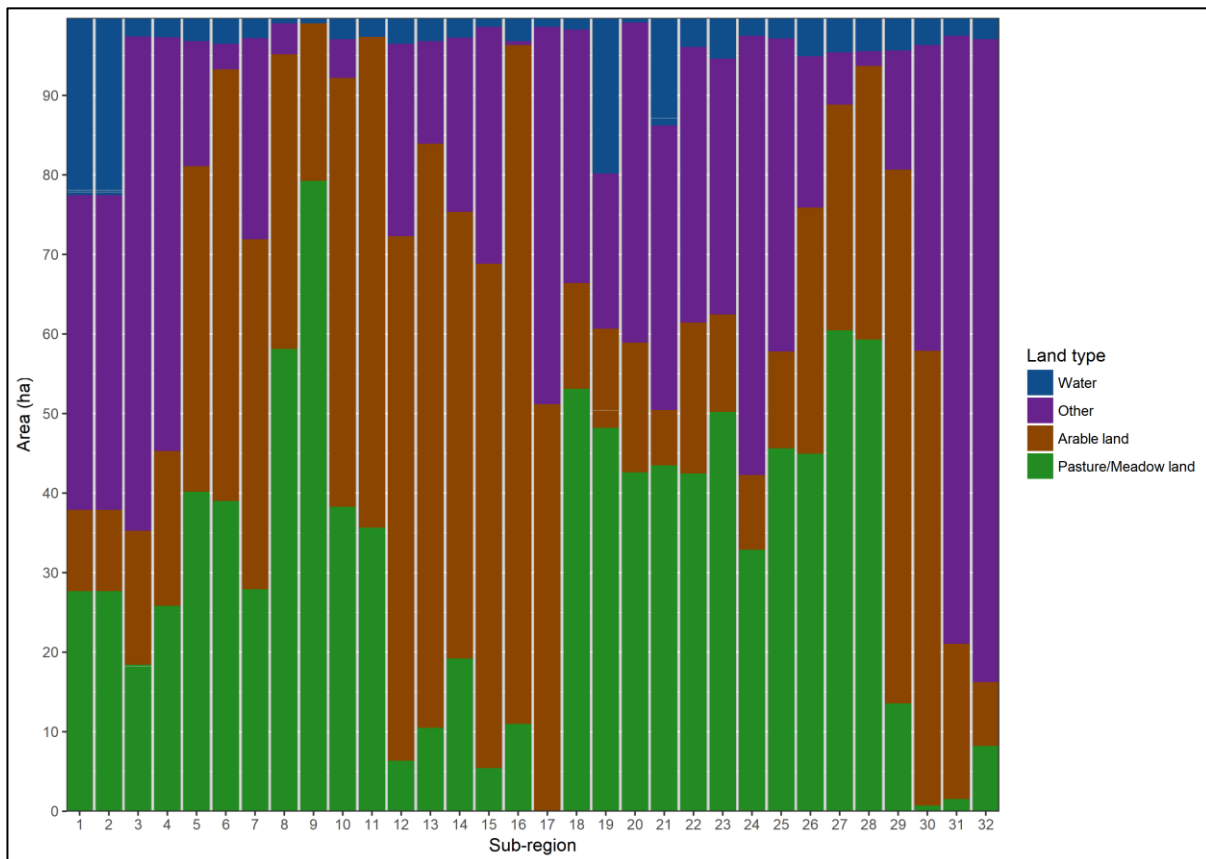


Figure 7.2. Proportion of potential arable land and flood basin, as well as landscape elements that are not assumed to be used in agriculture (other/water).

expanses of eutrophic peat dominated the coverage of these sub-regions which would have contained large areas of fen woodland consisting mostly of alder carrs (van Dinter 2013; Kooistra *et al.* 2013). Settlements located in these sub-regions therefore were advantaged by the substantial quantity of wood in their vicinity which would have been exploited extensively for both timber and firewood (Kooistra *et al.* 2013, 10). In the central region (sub-regions 5-11 and 27 & 28), the corridors of higher parts of the landscape broaden slightly, particularly in the northern region, thereby increasing the areas of land suitable for habitation and arable farming, however suitable land remained limited. The coverage of floodplain that could be exploited as pasture or meadow land is at its greatest in these sub-regions reducing land limitations on animal husbandry significantly. The sub-regions in the easternmost part of the study region (sub-regions 12-17 and 29 & 30) comprised much wider areas of levee that were used for habitation and arable farming and only very little coverage of floodplain. The reduced availability of grassland for pasture and fodder production would likely require the use of the higher parts of the landscape for animal husbandry in addition to arable farming and habitation. In the north and south of the eastern part of the study region, large areas of cover sands and Pleistocene sands were present. Some relict woodland may have been present here (Kooistra 2008a). In addition, arable farming may have taken place on these poorer soils. The final two sub-regions (sub-regions 31 & 32) are also located in this eastern region however the area of landscape such as levees that were used elsewhere in the region for living grounds and arable farming are much reduced, and the availability of floodplain is scant too. These two sub-regions comprise coversands, high Pleistocene sands and fluvial terraces.

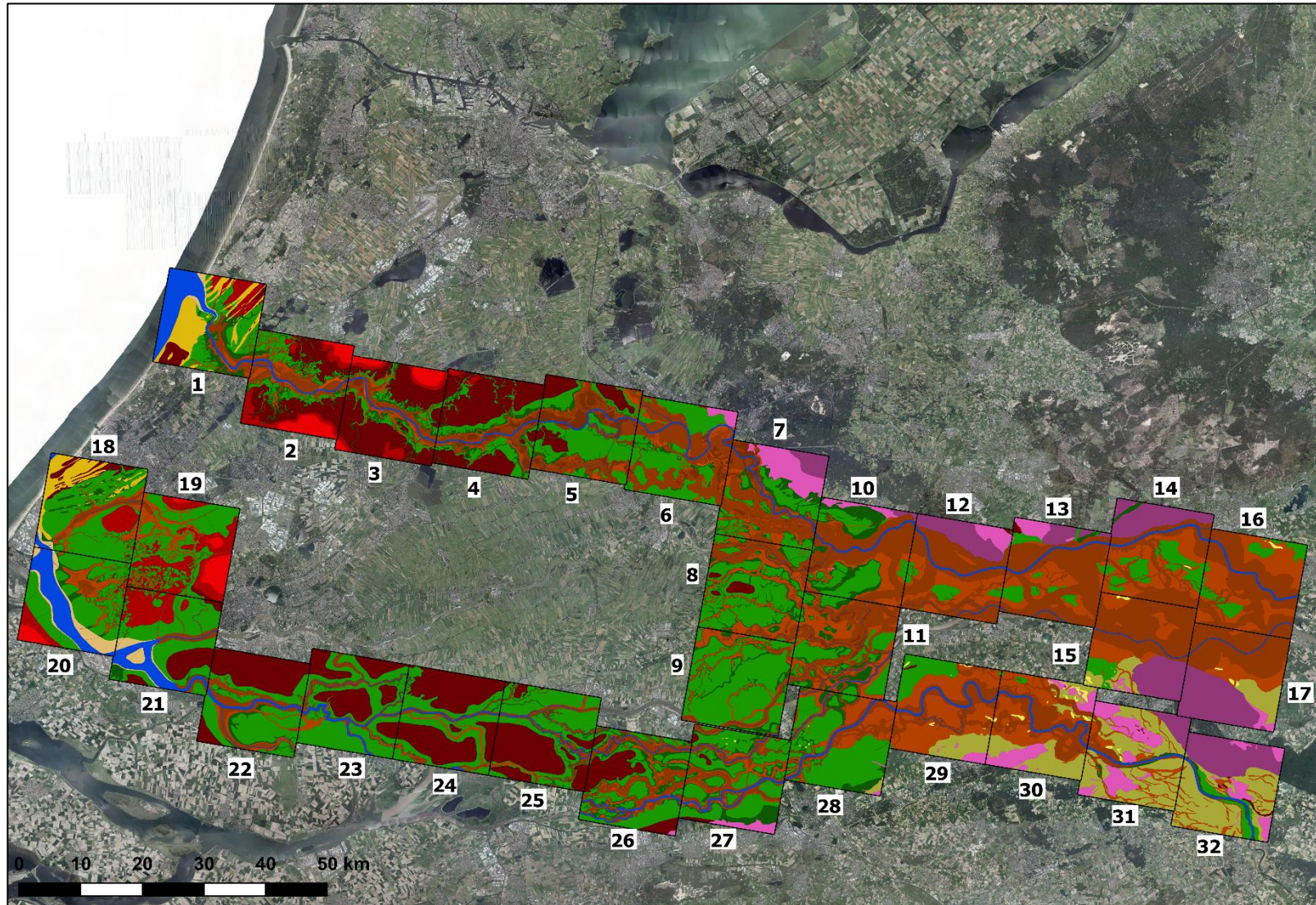


Figure 7.1. Palaeogeographic reconstruction of the thirty-two sub-regions used in this study. Data from Groenhuijzen (2018). ■ Sea/river/lakes; ■ High levee; ■ Moderately high levee; ■ Low levee; ■ Very low levee/residual gully; ■ High floodplain; ■ Low floodplain; ■ Eutrophic peat; ■ Mesotrophic peat; ■ Oligotrophic peat; ■ Dunes and beach ridges; ■ Tidal flats; ■ High Pleistocene sands; ■ Coversand; ■ River dune; ■ Fluvial terraces

Although throughout the sub-regions, uniform uses of some landscape types have been assumed (after Groot & Kooistra 2009), differences in the natural landscape from the coast to the eastern border of the study area offered both advantages and disadvantages for rural settlements, therefore. In the coastal regions, the presence of unique coastal landscape elements such as dunes and tidal flats could have been exploited for both arable farming and animal husbandry, especially advantageous in the case of arable farming given the limited area of levees. Inland in this western part of the Dutch *limes* zone, the narrow corridors of the higher parts of the landscape and floodplain would have presented significant limitations on both arable farming, animal husbandry and living space. However, the large swathes of eutrophic peat would have provided extensive fen woodland to be exploited by settlements, with woodland scarce elsewhere in the study region. In the central area, the higher parts of the landscape remained as narrow corridors and thus limiting arable farming, however the extensive floodplains present would have offered substantial pasture and meadow land for animal husbandry. In the eastern part of the study region, the areas of land suitable for arable farming and habitation broaden but settlements would have had only limited access to the rich grasslands for animal husbandry compared to those sub-regions to the west. Area of cover sands and Pleistocene sands to the north and south may also have been exploited for arable farming despite being nutrient poor and some relict woodland may have remained which could be exploited for timber and fuel. In the extreme south-easterly limits of the study region, those elements of the landscape assumed to have been used for arable farming, habitation and floodplains were scant and exploitation of fluvial terraces, cover sands and Pleistocene sands would have been necessary for all elements of the agricultural economy.

The size of each sub-region is uniform with each covering an area of 100km². The majority of settlements located in these sub-regions will therefore have access to all of the landscape within a 10km radius or a four hour round trip assuming 5km/hr walking speed (see chapter 4 section 4.3.6). A foraging radius of up to 10km is often cited as the distance travelled from a residential area for both foraging and collection (see Morgan 2008, 247), with fuel-timber collection simulated as a foraging behaviour in ROMFARMS. Obviously, for settlements located in the periphery of these sub-regions, parts of the landscape will be outside of a 10km radius. This would disadvantage these settlements when required resources (arable, pasture and meadow land, or woodland) were outside a 10km radius of the settlement. Such disadvantages are not discussed in this study, however. Not all rural settlements within the data-set are covered by these sub-regions, however. Some settlements in the eastern region of the study area in particular are not included within the sub-regions owing to how the study region has been sub-divided. In addition, the very sparsely populated peat areas in the centre of the study region have not been included within a sub-region. These missing settlements have an impact on any calculated land use and agricultural production for the whole study region.

7.1.2. Settlement occupation

In addition to differences in the natural landscape, the sub-regions used differ regarding settlement history with variations in the presence of the military and civilian settlements as well as variation in settlement density. Furthermore, within sub-regions, diachronic variation in settlement density and the extent of military and/or civilian presence is apparent from the archaeological record. These temporal and geographic variations in settlement history warrant discussion owing to their impact on supply of surplus produce from rural settlements and demand for grain and animal products from military settlements and *vici* within the sub-regions simulated. This is in addition to the broader trends in settlement occupation provided in chapter 2 (see section 2.2).

7.1.2.1. Uncertainties in the data-set

Given that the agricultural production in the study region is assumed to have been undertaken solely by rural settlements, the accuracy of the settlement dataset used has important ramifications for the extent of uncertainty in comparisons of potential rural agricultural supply and agricultural demand from military settlements and civilian settlements. Explicit acknowledgement of uncertainties in the data-set is essential, therefore. A number of possible uncertainties exist in the data-set used for this study including uncertainties regarding interpretation of sites, location, chronology and site size. The data-set used in this study and in the ‘Finding the limits of the *limes*’ project consists mainly of data available from ARCHIS, maintained by the *Rijksdienst voor het Cultureel Erfgoed* (National Cultural Heritage Service RCE) in the Netherlands. This data takes the form of ‘find spots’, with a concentration of ‘find spots’ (≥ 10) within 250m of a centre being a site (after Verhagen *et al.* 2016b; see also Bloemers 1978; Willems 1984; van Es 1994; Vos 2009). A site type must be inferred from characteristic evidence (if at all present) therefore. Given that a site is denoted in the data-set as a concentration of find spots within a certain radius of a centre, this centre must be defined. The find spot with the highest number of finds is determined as the centre in this study (see Verhagen *et al.* 2016b). It was noted however in Verhagen *et al.* (ibid., 310) that owing to precision in the location of find spots, locational uncertainties were ‘usually not very serious’. Imprecision regarding settlement location is unlikely to place a settlement in the incorrect sub-region, therefore. ROMFARMS does not simulate using actual settlement locations, but simulates settlements based on observed densities in each settlement. This was because ROMFARMS was not developed to emulate actual settlement patterns in the past and, furthermore, high-resolution data related to chronological and geographic development of settlements in each micro-region is not available. Settlements are therefore placed randomly in the landscape meaning that accurate settlement locations are not necessary. Another type of uncertainty which is potentially more serious is uncertainty with chronology. In ARCHIS, exact dating is not used and find spots are defined by periods, some of which span relatively long periods e.g. “Roman” (462 years) or “Middle Roman” (200 years) and others not, e.g. “Early Roman B” (37 years) (see table 7.1 for periods used in this study). Verhagen *et al.* (ibid.) found that more than 40% of sites in their data-set had dating that was unable to provide clear conclusions about chronological development of the site. In addition, the research highlighted the possibility of over- or under-estimation of the number of settlements in each period. The size of sites is also uncertain because they are identified by find spots. Surface finds do not provide evidence of the possible size of a settlement nor the number of households within a settlement nor the possible number of people living there. Lastly, it can be presumed that many settlements are missing from the archaeological record owing to post-Roman erosion or because they have yet to be discovered. For the Kromme Rijn region, Vos (2009, 33) estimated that approximately 15% of archaeological sites are missing from the data-set for these reasons and it is probable that other regions also suffer from similar numbers of missing sites or even more.

PERIOD	IJZL	ROMV		ROMM	
	LATE IRON AGE	EARLY ROMAN		MIDDLE ROMAN	
	–	ROMVA	ROMVB	ROMMA	ROMMB
DATE	250–12 BCE	12 BCE–25 CE	25–70 CE	70-150 CE	150-270 CE
TIME SPAN	238	37	45	80	120

Table 7.1. Periods and associated time spans (periods correspond to ARCHIS periods).

There are therefore uncertainties concerning the number of settlements, the number of settlements that can be correctly identified as rural, food-producing settlements, the number of

settlements in each period, the size and number of inhabitants in settlements, and, to a lesser extent, the location of settlements. These uncertainties have impacts on the assessment of agricultural production within sub-regions. Underestimation or overestimation of the number or size of agrarian rural settlements in each sub-region and period would result in an underestimation or overestimation of the potential surplus of grain or animal products produced by rural settlements as well as land use for animal husbandry and arable farming. In short, the data-set used is not a complete list of rural settlements in the Dutch *limes* zone from the Late Iron Age to the end of the Middle Roman period which necessarily limits how representative any conclusions are of agricultural productivity in the past. However, it is envisaged that the continued improvement or ‘correction’ of uncertainties of the data-set and additions to the data-set will enable more representative conclusions to be made.

Although some of the uncertainties relating to military and civilian settlements are provided below in the description of *castella* and *vici*, some general remarks can be made. Firstly, knowledge of military and civilian sites in the Dutch *limes* zone can be somewhat limited owing to problems with documentation. In particular, excavations before the 1970s were often poorly documented, with only succinct reports remaining in often inaccessible journals. Whilst documentation improved from the 1980s onwards, there remain issues with variable accessibility of literature. More problematic are the uncertainties regarding dating of occupation. Excavations of some sites have permitted relatively accurate dating for foundation, rebuilding and abandonment, however for others occupation dates are estimates. Often a date of approximately 50 CE was given which corresponds to Corbulo’s activities in Germania Inferior from 47 CE (Tacitus *Ann.* 20.19-20) but is rarely more than a best guess. Equally, most military and civilian settlements are assumed to have been occupied until 270-275 CE coinciding with the severe weakening of the Rhine border. However, evidence for occupation of *castella* is limited after the reign of Septimius Severus i.e. from 211 CE onwards. Lastly, there remain significant uncertainties relating to the presence of military or civilian settlements in the southern part of the study region and in particular Gelderland. Some *castella* and *vici* have been hypothesized or inferred from limited evidence, however their existence remains uncertain. The presence of a military or civilian settlement in a sub-region has an impact on calculations of estimated demand. These settlements are not simulated by ROMFARMS and therefore their presence only is used. The actual locations of consumer-only settlements in sub-regions is not required. Uncertainties in dating and number of *castella* and *vici* will have ramifications for the assessment of military and civilian demand for surplus both temporally and geographically. As in the case of uncertainties in the data-set of rural settlements, the continued attempts at improving and expanding the data-set and correcting uncertainties where possible will increase how representative it is of the situation in the Dutch *limes* zone during the Roman period. This in turn will improve the robustness of any conclusions made regarding the economy of the region in future research.

7.1.2.2. Rural settlements

Settlement density in each of the sub-regions reconstructed for ROMFARMS is not uniform and trends in those broader subdivisions of the Dutch *limes* region used above can be identified. In most regions, an increase in the number of settlements over time can be observed from the evidence of rural settlements. In a majority of sub-regions, an increase in settlement density occurs from the Late Iron Age to the Early Roman period and again from the Early Roman period to the Middle Roman period. In only a minority of sub-regions do the number of settlements decrease and then only in the transition from the Early Roman period to the Middle Roman period and between the Middle Roman periods A and B. During the Early and Middle Roman periods, the majority of sub-regions experience no change in settlement density between subperiods A and B.

The number of settlements differs also among sub-regions geographically. Settlements in the Iron Age were largely confined to the central and eastern areas (sub-regions 7-17 & 27-32) with only limited occupation in the western coastal region and estuaries of the rivers Rhine and Maas (sub-regions 1 & 18-21). Those sub-regions characterised by narrow levees flanked by broad areas of peat (sub-regions 2-4 & 22-25) possessed no settlements except for sub-regions 2 and 23. This trend continues throughout the Roman period, with only a handful of settlements present even during the Middle Roman period when the total number of settlements in the entire study region is at its highest. In other sub-regions, the number of settlements continue to increase from the Late Iron Age onwards, with the central and eastern sub-regions (see above) becoming relatively densely occupied by the Middle Roman B period. In the coastal regions, the number of settlements increases after the Late Iron Age, with sub-region 18 becoming relatively densely occupied by the end of the Middle Roman period.

In ROMFARMS rural settlements are only placed on the levees in the simulated landscape following a simplification of Groot & Kooistra's (2009) interpretation of landscape use. The majority of settlements (c. 67%) were indeed located on levees of differing elevations during the Late Iron Age and Roman periods, however a small minority of sites were also located on the cover sands and High Pleistocene sands in the eastern regions and floodplains in the central sub-regions. Very few settlements were located on the dunes and beach ridges of the coastal regions or on peat located in the western half of the study region although this could also be an issue with preservation and discovery. There is a strong correlation between habitation and the levee parts of the landscape (see also Verhagen *et al.* 2016b and Groenhuijzen 2018). Settlement density per sub-region is provided in table 7.2. A distinction has been made between settlement density for the total area of land within sub-regions and settlement density for the total area of landscape elements assumed to be habitable in ROMFARMS i.e. levees or stream-ridges. The corresponding settlement densities used in ROMFARMS simulations are also provided. Settlement densities used in ROMFARMS are slightly in excess of those in the data-set, however. This is because the resolution of the GIS rasters used is much greater than can be successfully implemented in NetLogo. As a result, ROMFARMS reconstructed landscapes are a trade-off between what NetLogo can successfully simulate and detail. ROMFARMS' reconstructions of the palaeogeography of subregions lose some detail causing a small reduction in the total area of simulated landscapes. Accordingly, settlement density increases. This is likely to have an impact on conclusions regarding land use in each of the sub-regions, particularly when gauging the extent that land availability limited agricultural production, as considered above. In addition, owing to in-built rules in ROMFARMS, settlement density in each sub-region is adjusted to enable at least four settlements to occupy a landscape in any one sub-region. A settlement density that restricts the number of settlements to less than 4 per km², prevents the simulation reaching 100 years in a majority of simulation runs.

SUB-REGION	ACTUAL NO. SETTLEMENTS/INHABITABLE AREA					ROMFARMS NO. SETTLEMENTS/INHABITABLE AREA				
	IJZL	ROMV A	ROMV B	ROMM A	ROMM B	IJZL	ROMV A	ROMV B	ROMM A	ROMM B
1	0.98	1.47	1.56	1.86	1.76	1.41	2.12	2.26	2.68	2.54
2	0.23	0.86	0.86	0.95	0.95	0.34	1.27	1.27	1.41	1.41
3	0.00	0.00	0.06	0.18	0.18	0.00	0.00	0.35	0.35	0.35
4	0.00	0.00	0.00	0.00	0.05	0.00	0.00	0.00	0.00	0.30
5	0.51	0.78	0.83	0.78	0.73	0.75	1.14	1.22	1.14	1.07
6	0.48	0.72	0.72	0.88	0.86	0.70	1.06	1.06	1.30	1.27
7	0.57	1.00	1.00	1.29	1.29	0.83	1.47	1.47	1.90	1.90
8	0.08	0.43	0.46	0.89	0.89	0.16	0.63	0.67	1.29	1.29
9	0.40	1.01	1.01	1.41	1.41	0.59	1.48	1.48	2.07	2.07
10	0.28	0.46	0.46	0.57	0.57	0.41	0.68	0.68	0.84	0.84
11	0.44	0.97	0.99	1.28	1.28	0.64	1.42	1.44	1.87	1.87
12	0.32	0.56	0.56	0.79	0.79	0.46	0.82	0.82	1.15	1.15
13	0.26	0.43	0.45	0.43	0.42	0.38	0.64	0.66	0.64	0.62
14	0.39	0.46	0.46	0.51	0.48	0.57	0.68	0.68	0.75	0.70
15	0.44	0.63	0.63	0.66	0.68	0.65	0.92	0.92	0.97	0.99
16	0.23	0.28	0.29	0.28	0.28	0.34	0.41	0.43	0.41	0.41
17	0.18	0.21	0.21	0.23	0.23	0.26	0.31	0.31	0.34	0.34
18	0.30	1.43	2.03	3.00	2.85	0.44	2.08	2.95	4.38	4.16
19	0.24	0.80	0.80	1.04	1.28	0.47	1.17	1.17	1.52	1.87
20	0.06	0.43	0.61	0.98	1.16	0.37	0.64	0.92	1.47	1.75
21	0.57	2.15	2.15	2.87	2.44	0.85	3.18	3.18	4.25	3.61
22	0.00	0.05	0.05	0.05	0.05	0.00	0.31	0.31	0.31	0.31
23	0.08	0.41	0.41	0.98	0.98	0.48	0.61	0.61	1.45	1.45
24	0.00	0.00	0.00	0.43	0.43	0.00	0.00	0.00	0.63	0.63
25	0.00	0.08	0.08	0.16	0.16	0.00	0.47	0.47	0.47	0.47
26	0.03	0.23	0.23	0.61	0.64	0.19	0.33	0.33	0.90	0.95
27	0.32	0.63	0.63	0.77	0.77	0.47	0.93	0.93	1.14	1.14
28	0.12	0.46	0.49	0.46	0.46	0.17	0.67	0.71	0.67	0.67
29	0.56	0.68	0.70	0.71	0.68	0.83	1.00	1.02	1.05	1.00
30	0.65	0.70	0.70	0.68	0.68	0.95	1.02	1.02	1.00	1.00
31	1.12	1.53	1.64	1.79	1.74	1.65	2.25	2.40	2.62	2.55
32	1.12	2.24	2.24	2.11	1.99	1.62	3.24	3.24	3.06	2.88

Table 7.2. Settlement density (no. settlements per km²) per region per period. Settlement densities are given as the number of settlements per area of inhabitable land (levees and stream ridges); and the number of settlements per area of inhabitable land in reconstructed sub-regions in ROMFARMS.

7.1.2.3. Military settlements and civilian settlements

Military settlements such as *castella* and *castra* and civilian settlements were present in only some sub-regions simulated in ROMFARMS. Throughout this chapter, consumer settlements are denoted as military or civilian settlements. Here civilian settlements are towns and *vici* whose inhabitants were not engaged in producing their own food and therefore distinct from rural, native settlements engaging in agriculture. The location and time-spans of occupation are

provided in table 7.3. Uncertainties concerning the existence of some sites and occupation dates still exist for the data-set of military settlements, however.

The line of fortifications that extended from the coast to the eastern edge of the study region in the Netherlands i.e. the *limes* proper began in the western coastal region (sub-region 1) with a *castellum* and *vicus* at Katwijk aan Zee (Brittenburg). The *castellum* probably corresponds to Lugdunum (Lugduno) in the *Tabula Peutingeriana*, one of only two extant sources with travel distances (the other being the *Itinerarium Antonini*), and one of only a handful of sources containing place names. Significant effort has been made in previous research to assign names mentioned in various ancient and medieval sources to known military settlements in the Dutch *limes* zone with various arguments put forward (see Joosten 2003; Buijtenorp 2010; Verhagen 2014). Whilst of toponymical interest, the archaeological importance of assigning ancient names to sites is not great. An exception to this are *castella* identified in the southern part of the study region in the province of Gelderland using sources below, whose identification as *castella* is not certain and therefore has a direct impact on the assumptions relating to demand in relevant sub-regions. The *castellum* at Katwijk aan Zee is now located a few hundred metres off the coast with two possible locations suggested by Parlevliet (2002) and Knul & van Zoeren (2012). Dating of occupation is uncertain but c. 50-250 CE seems probable. Excavations in 1982 unearthed a possible *vicus* occupied from 160-240 CE (Bloemers & de Weerd 1984). Some five to seven kilometres inland along the *limes* road,² the *castellum* of Valkenburg (*Praetorium Agrippinae*) is located (also sub-region 1). It was built in 39/40 CE, destroyed in 70 CE during the Batavian revolt, rebuilt in stone in 180 CE and abandoned sometime between 240 and 275 CE (de Hingh & Vos 2005). Valkenburg's *vicus* is located to the south at the site of Marktveld-Veldzicht-De Woerd (de Hingh & Vos 2005; see also Vos *et al.* 2012).³ A 'mini-*castellum*' was also found at Marktveld occupied between 70 and 110 CE (de Hingh & Vos 2005).

Between seven and nine kilometres east of Valkenburg lay Leiden Roomburg, identified as *Matilo*. The *castellum* here was constructed after 70 CE D and at least before 85 CE, rebuilt in stone before 196-198 CE and deserted sometime between 240-260 CE (see Brandenburgh & Hensing 2005; Polak *et al.* 2004a). A large *vicus* was alongside and occupied from approximately 70-250 CE (Hazenbergh 2000). The next *castellum* is located in sub-region 3 approximately 10 to 13km from Leiden-Roomburg. Alphen aan den Rijn, identified as *Albaniana*, was identified as a *castellum* in 1998 by Haalebos & Franzen (2000). The *castellum* was constructed in 40-41 CE and remained occupied until 270-275 CE with reconstruction in stone around 160 CE (Polak *et al.* 2004b; Kemmers 2004). The associated *vicus* is supposed to have been occupied 80-275 CE at Hoge Zijde I (Kok 2001). Zwammerdam (*Nigrum Pullum*) was located approximately four to five kilometres further east from Alphen aan den Rijn (sub-region 3) and was occupied from approximately 47 CE until 270-275 CE with a rebuilding in 80 CE and 175 CE (see Glasbergen & Haalebos 1968; de Weerd & Haalebos 1973 for excavation reports). A *vicus* was present south and east of the *castellum* and occupied from the Early Roman period B to the end of the Middle Roman period, therefore c. 70 CE – 270 CE perhaps. The final *castellum* that has been identified with some ease from the *Tabula Peutingeriana* is Woerden (*Laurium*) located in sub-region 4 approximately 12-16km from Zwammerdam. The *castellum* was probably constructed between 43 and 47 CE and deserted 270-275 CE, with a *vicus* growing from 70 CE west of the *castellum* (Blom & Vos 2008). Between Zwammerdam and Woerden, finds from Bodegraven (sub-region 3)

² Joosten (2003), Buijtenorp (2010), van Dinter (2013) and Verhagen (2013) have reconstructed distances between military settlements along the military road provided by the *Tabula Peutingeriana* and the range given corresponds to different reconstructions. Distances provided by the *Tabula Peutingeriana* are given in Gallic leagues which roughly correspond to a distance of 2.22km. Beyond Woerden (*Laurium*), distances from the *Tabula Peutingeriana* are more difficult to interpret and therefore distances are not given and Roman names are sometimes more tentative.

³ Three different sites have been excavated which correspond to a single settlement.

pointed to a military presence between 1st to middle 3rd century (Beunder 1980; Bogaers 1980a, Haalebos 1980). Bodegraven was initially considered the site of a 'mini-castellum' but newer interpretations by Vos *et al.* (2016) suggest Bodegraven was a full *castellum*.

East of Woerden, identification of *castella* from names given by the *Tabula Peutingeriana* becomes more difficult, with implications for the possible distances along the *limes* road between sites. In sub-region 5 lies the *castellum* at Vleuten-De Meern. The remains of the *castellum* and a *vicus*, in addition to other Roman remains, have been intermittently excavated from 1940 to 1983 (Langeveld *et al.* 2010). The fort was constructed in 40 CE and deserted between 270-275 CE. The *vicus* developed sometime in the Flavian period until the end of the 3rd century (*ibid.*).⁴ In sub-region 6 lies Utrecht (Traiectum). The *castellum* at Domplein in the centre of modern Utrecht was constructed around 50 CE and deserted c. 275 CE with reconstructions between (Ozinga *et al.* 1989). A *vicus* was present and developed after 70 CE, with occupation continuing until the *castellum* was abandoned (Montforts 1991). Continuing east, the *castellum* at Vechten (also in sub-region 6) was the oldest and largest *castellum* in the Netherlands probably built between 5 BCE and 0 CE, and occupation continued until after 225 CE (Zandstra & Polak 2012). It housed a double-sized cohort (van Dinter *et al.* 2014). A *vicus* was also present from after the Batavian revolt in 70 CE until the end of the occupation of the *castellum* (Zandstra & Polak 2012). In sub-region 10, a probable *castellum* at Maurik was been inferred on the basis of remains dredged from the Rhine floodplain (Bogaers & Haalebos 1972). Occupation before 70 CE can not be proved and the *castellum* was probably deserted c. 270-275 CE (for beginning of military presence here see Haalebos 1976; 1986). Furthermore, there was no indication for a *vicus*. Also, in sub-region 10, a *castellum* but no *vicus* possibly existed at Rijswijk and was inferred again from finds dredged from the Rhine floodplain (van Es 1984). Dating of the finds indicated that occupation was from 50 CE. The existence of a *castellum* at Rijswijk remains uncertain however although probable building material was re-used in the construction of Dorestad (van Es & Verwers 2010). Also uncertain, but perhaps more probable, was a *castellum* at Kesteren in sub-region 12. A *castellum* was inferred by Bogaers & Rüger (1974). It was probably occupied from 50-225 CE and a *vicus* was probably enlarged around 70 CE and abandoned at the same time as the *castellum* (Hulst 1986).

A *castellum* at Randwijk in sub-region 13 was hypothesized by Willems (1986) although no remains were ever found and is not included in this data-set. A *castellum* at Arnhem-Meinerswijk in sub-region 14 is certain. The *castellum* at Arnhem-Meinerswijk was one of the earlier *castella* in the Netherlands built probably between 14-16 CE (Willems 1980). There was a probable gap in use until the Claudian period and it was finally deserted at the end of the 3rd century. A *vicus* attached to Arnhem-Meinerswijk is not present in the data-set. The substantial military and civilian settlements associated with modern Nijmegen are spread across sub-regions 15 and 17. In sub-region 15, lie the two civilian settlements of Nijmegen: a *vicus* at Valkhof (Oppidum Batavorum) and the *civitas* capital of Ulpia Noviomagus. The site at Valkhof is the earlier of the two and developed from 10 CE into a large settlement until its destruction in the Batavian revolt (van Enckevort & Heirbaut 2010). After the Batavian revolt, the civilian settlement moved to the site at Waterkwartier which became Ulpia Noviomagus. The site was possibly elevated to *municipium* status c. 100 CE (Willems & van Enckevort 2009; Haalebos 2000) and occupied until around 275 CE. The military settlements of Nijmegen are contained in sub-region 17. The earliest military settlement was built at the Hunerberg in 19 BCE and was dismantled at the latest 10 years later but probably earlier (Willems & van Enckevort 2009). Around 12 BCE, a smaller military camp was built on the Kops Plateau, becoming a *castellum* proper in 10 CE and remaining in use until the Batavian revolt (van Enckevort & Zee 1996). After the revolt, the Xth legion was stationed at the Hunerberg where a *castra* was constructed, leaving

⁴ Dates are accordingly estimated as 70-270/275 CE.

it in 103 or 104 CE. After this event, it is unlikely that a significant military presence remained (Haalebos 2000; Willems & van Enckevort 2009). In sub-region 16, military presence at Loowaard was identified via finds found after dredging which may indicate the presence of a *castellum*. If so, it was a relatively early *castellum* (founded tentatively around 40 CE) that remained occupied until the collapse of the *limes* (van Dockum 1995).

Military and civilian settlements in the southern part of the study region are more problematic to identify. The exception is Forum Hadriani located in modern Voorburg. The location of Voorburg falls outside the sub-regions used in ROMFARMS, however its importance as a major civilian settlement warrants its inclusion in any assessment of agricultural demand in the study region. It has been included therefore in sub-region 18. Occupation at Forum Hadriani may have begun in the first half of the 1st century AD. After 85 CE, the site expanded and probably became the *civitas* capital of the Cananefates. The town was probably largely depopulated by 275 CE on account of economic decline and political crises in the Roman Empire (de Jonge *et al.* 2006). In sub-region 18 a 'mini-castellum' at Ockenburgh was located that was occupied from 150-180 CE and a *vicus* with a longer occupation to 250 CE (Waasdorp 2012; van Zoolingen 2015). The only remaining *vici* or *castella* located in the southern part of the study region are located in Gelderland (sub-regions 28 & 32). A possible *castellum* and *vicus* may have been located at Alem-Rossum. A civilian settlement here is more certain with Roymans (2004, 144-146) identifying a site of supra-regional significance here. The possibility of a *castellum* is very uncertain and is not considered in the following discussion (see van Hemert 2010). The settlement at Lith De Bergen may have been a *vicus* in the Roman period and probably an important Iron Age site before that (see Roymans 2004). Lastly, in sub-region 32, a settlement at Cuijk has been proposed as a *vicus* starting in the mid-first century until the collapse of the *limes* as the Rhine border. Despite references to a *castellum* at Cuijk also (see Bogaers 1966; van Enckevort & Thijssen 2002; Haalebos *et al.* 2002), evidence is limited and points to only a very short military presence there.

PLACE	SUB-REGION	SITE TYPE	IJZL	ROMVA	ROMVB	ROMMA	ROMMB
KATWIJK	1	Castellum					
KATWIJK	1	Vicus					
VALKENBURG	1	Castellum					
VALKENBURG	1	Vicus					
VALKENBURG	1	Mini-castellum					
LEIDEN	2	Castellum					
LEIDEN	2	Vicus					
ALPHEN AAN DEN RIJN	3	Castellum					
ALPHEN AAN DEN RIJN	3	Vicus					
BODEGRAVEN	3	Mini-castellum					
ZWAMMERDAM	3	Castellum					
ZWAMMERDAM	3	Vicus					
WOERDEN	4	Castellum					
WOERDEN	4	Vicus					
DE MEERN	5	Castellum					
DE MEERN	5	Vicus					
UTRECHT	6	Castellum					
UTRECHT	6	Vicus					
BUNNIK	6	Castellum					
BUNNIK	6	Vicus					
MAURIK	10	Castellum					
RIJSWIJK	10	Castellum					
KESTEREN	12	Castellum					
KESTEREN	12	Vicus					
ELDEN	14	Castellum					
NIJMEGEN	15	Vicus					
NIJMEGEN	15	Civitas capital					
LOO	16	Castellum					
NIJMEGEN	17	Castellum					
NIJMEGEN	17	Castrum					
NIJMEGEN	17	Castrum					
LOOSDUINEN	18	Mini-castellum					
VOORBURG	18	Civitas capital					
ALEM	28	Vicus					
LITH	28	Vicus					
CUIJK	32	Vicus					

Table 7.3. List of civilian (*vici*, *civitates capitals*) and military (*castella*, *mini-castella* and *castra*) in data-set, the sub-regions they are located in and period of occupation.

7.2. Limiting factors in reconstructed landscapes

In the previous two chapters, an analysis of subsistence-based and surplus agricultural production strategies was provided to gauge the relative importance of different factors that rural settlements could have been limited by. Evaluating the availability of suitable land for agricultural activities was not possible in those analyses however owing to the use of randomly-generated and unrealistic landscapes. As these landscapes are not representative of the Dutch *limes* zone in the Late Iron Age or Roman periods, any conclusions relating to the availability of land as a limiting factor in agriculture in the study region would be equally as unrepresentative. In the following section, subsistence-based and surplus agricultural production are therefore analysed once again in the reconstructed sub-regions with the data-set of rural settlements described above.

7.2.1. Arable land use

It is worth repeating here how the area of land cultivated by rural settlements is determined under each of the arable farming strategies. When settlements undertake subsistence-based arable farming, the area of land cultivated is a direct function of the number of inhabitants, the proportion of their diet that is grain-based and the size of the buffer. Settlements undertaking intensification will not cultivate any more arable land than they would under a subsistence-based strategy. Under extensification, in addition to the area of land necessary to produce grain for the needs of the inhabitants, settlements will cultivate more land provided they have access to sufficient land, labour and sowing-seed. Settlements undertaking extensification or subsistence-based farming must also practice biennial fallowing. The area of land that settlements need access to is therefore approximately twice the area of land that is cultivated: half to be sown in one year and half to be left fallow from the previous year's arable farming (not accounting for fluctuations in the area of land cultivated each year). It can be expected therefore that the total area of land would be largest in landscapes simulated with large settlements undertaking extensification. The total area of land cultivated would be smallest in landscapes occupied by only small settlements with single households undertaking subsistence-based farming or intensification.

To assess whether the availability of land was a limiting factor for rural settlements in each of the sub-regions, the area of arable land available and the area cultivated each year were compared. In landscapes with settlements undertaking either subsistence-based arable farming or arable extensification, if the total area of arable land cultivated is greater than 50% of the available suitable land for arable farming i.e. levees or stream ridges, availability of land becomes a limiting factor. Settlements undertaking these two strategies must also undertake biennial fallowing and therefore need access to double the area of land that will be cultivated each year. In scenarios where rural settlements undertake intensification, there is no requirement for fallowing. Then, a shortage of land will only be experienced should the total area of arable land available in a sub-region be less than the total area that needs to be cultivated.

7.2.1.1. Arable land use in the Dutch *limes* zone

In scenarios simulating the Late Iron Age, it has been assumed that settlements undertook subsistence-based farming. Settlements cultivated only sufficient land to produce enough grain for the own consumption needs, sowing seed for the following year and a small surplus, or buffer. The total area of land cultivated is therefore a direct function of the number of settlements and the number of inhabitants in each settlement. In sub-regions occupied by larger settlements with a higher absolute number of settlements, the total area of land cultivated each year will be higher than in other sub-regions. Simulating arable farming in randomly-generated landscapes however showed that settlements undertaking subsistence-based arable farming cultivate relatively small

areas of land. The total area of arable land cultivated each year in each sub-region is significantly lower than the total area of potential arable land that is available to settlements (see figure 7.3a). The proportion of arable land use is highest in sub-regions 1, 21, 31 and 32. In these regions, the area of potential arable land is comparatively small and for regions 31 and 32, the number of settlements is relatively high. However, arable land use remains very low. The highest proportion of available arable land used in any scenario is less than 10%. The availability of suitable arable land in each sub-region is therefore sufficient to prevent settlements experiencing any limitations in their ability to produce sufficient food for themselves, even in the unlikely scenario that landscapes of the past in the Dutch *limes* zone were occupied only by larger settlements containing five contemporary households.

For the Early and Middle Roman periods (12 BCE-270 CE), scenarios were simulated in which settlements undertake some form of surplus arable farming. A similar pattern can be observed from the results, however, which show that the proportion of the total arable land available that is cultivated each year remains relatively high in sub-regions 1, 21, 31 and 32 (see figures 7.3b-i). Increases in settlement density over time alters the pattern somewhat. A substantial increase in settlement density in sub-region 18 from the Late Iron Age to the Early Roman Period A, means that the proportion of the total arable land available that is cultivated also becomes comparatively high. The proportion of available land cultivated in sub-region 9 becomes comparatively high by the Middle Roman Period B, as does the proportion cultivated in sub-region 19 by the Middle Roman Period B also owing to increases in settlement density in these sub-regions.

Significant differences in land use in the Early and Middle Roman periods can be observed between scenarios wherein settlements undertake different arable strategies. As discussed in the previous chapter (see chapter 6 section 6.2.2), settlements undertaking intensification do not cultivate any extra land than would be cultivated under subsistence-based arable farming. In contrast settlements undertaking extensification will cultivate as much as extra land as the most limiting factor (the availability of sowing seed, labour or land) permits. Increases in land usage in sub-regions between periods when subsistence-based arable farming and periods when surplus arable farming is undertaken in scenarios with settlements undertaking intensification are owing to increases in settlement density and not owing to absolute increases in the area of land cultivated per settlement. In contrast, the relatively high proportion of land cultivated in each sub-region in scenarios with settlements practicing extensification is owing to both increases in settlement densities as well as absolute increases in land usage per settlement. The results show that, despite these increases in land usage, the proportion of the total area of available land that is cultivated by all settlements within most sub-regions and in each period, is significantly below the thresholds identified above. Arable land use by settlements undertaking intensification or subsistence-based arable farming is low enough that, even in densely populated sub-regions, only a small proportion of the total available area of arable land is used each year. The total area of land cultivated by settlements undertaking extensification is also lower than the 50% threshold in most scenarios. In some sub-regions, the median total area of land cultivated approaches 50% when these sub-regions are occupied by settlements with five households and the total area cultivated exceeded 50% in a minority of simulation runs. This could indicate that the availability of land in sub-regions was a limiting factor in these scenarios. Those sub-regions (1, 9, 18, 21, 31, 32) have comparatively small areas of potential arable land (see figure 7.2) as well as comparatively high simulated settlement densities (see table 7.3). It is therefore not unexpected that land represents a limiting factor in more simulation runs in those sub-regions than others.

Uncertainties in the data-set and difficulties when converting a data-set containing possible sites to actual settlement density restrict the robustness of any conclusions made

regarding land use. Reconstructed landscapes in ROMFARMS use a homogeneous occupation in which settlements all possess the same number of households. Furthermore, ROMFARMS utilises a maximum settlement density rather than absolute numbers of settlements in its simulations to restrict the number of settlements in each sub-region in a stochastic way. It is not assumed that the total number of settlements in the archaeological data-set in each sub-region for each period existed contemporaneously throughout the whole period. Rather, conversion of absolute settlement numbers to an upper limit of settlement density permits the simulation of a hypothetical maximum occupancy scenario that simulates maximum arable land use. The stochastic demographic sub-process permits the simulation of a hypothetical minimum occupancy scenario. Simulated land use in ROMFARMS does not accurately imitate land use in the past in the Dutch *limes* zone but the results have produced a possible range of values for arable land use with the actual land use falling within this range. The results can also indicate when restrictions on arable productivity because of limited availability of arable land could have occurred in the Dutch *limes* zone. Only in unrealistic scenarios where all settlements possess five households can the availability of land restrict settlements undertaking extensification and only then in a minority of cases. Thus, despite ROMFARMS being unable to accurately mirror the actual settlement history of landscapes of the Dutch *limes* zone in the past, it is probable that land availability was rarely the most limiting factor.

The results show that settlements were most limited by those factors identified from the results of simulating arable farming in randomly-generated landscapes. Settlements undertaking subsistence-based arable farming are therefore most limited by the availability of sowing seed (see chapter 5 section 5.2.3). Settlements undertaking either extensification or intensification are most limited by the availability of labour and manure respectively (see chapter 6 sections 6.2.1.1 & 6.2.2.1).

7.2.2. Pasture and meadow land

Animal herds in ROMFARMS require both pasture land for grazing during the majority of the year and fodder for winter that is collected by settlements from meadow land. Suitable land for grazing and fodder collection is assumed to lie primarily on flood basins located in sub-regions. In sub-regions with only very small areas of flood basin, the area of land suitable for animal husbandry is therefore limited. This could increase the likelihood that other landscape types are needed for animal herds including landscape types that are required for other activities, notably arable farming. To identify whether the availability of suitable land for animal husbandry could have been a limiting factor in the Dutch Roman *limes* zone, comparisons between the area required by settlements in each sub-region and the area available were calculated. The availability of land is determined as a limiting factor when more land is required than available. In addition, the analysis takes into account in which scenarios use of other landscape elements would have been necessary to undertake different forms of animal husbandry.

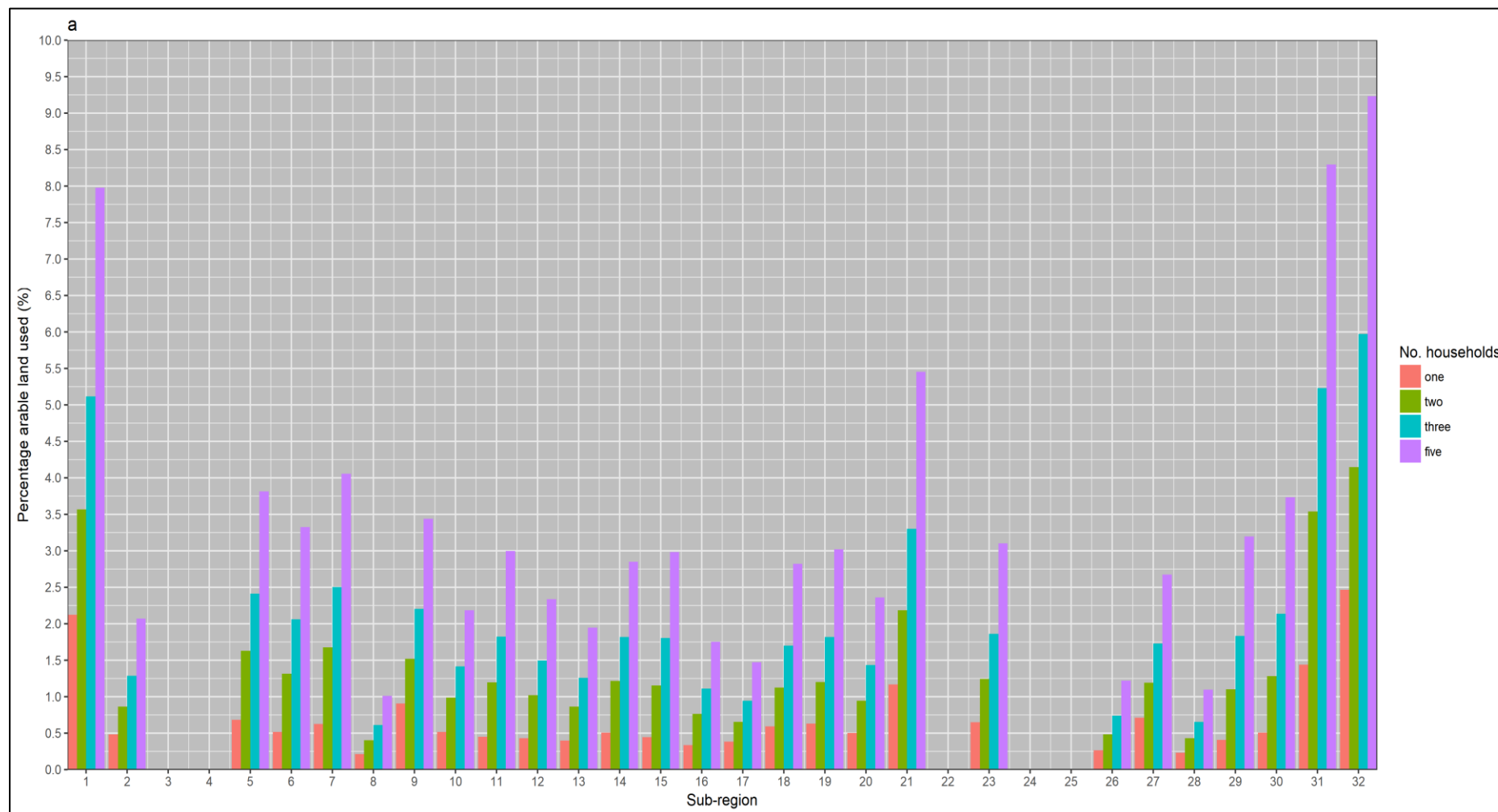


Figure 7.3a. Percentage of total available arable land used each year by settlements of different sizes undertaking subsistence-based arable farming per sub-region using reconstructed settlement densities from the Late Iron Age (250BCE-12BCE).

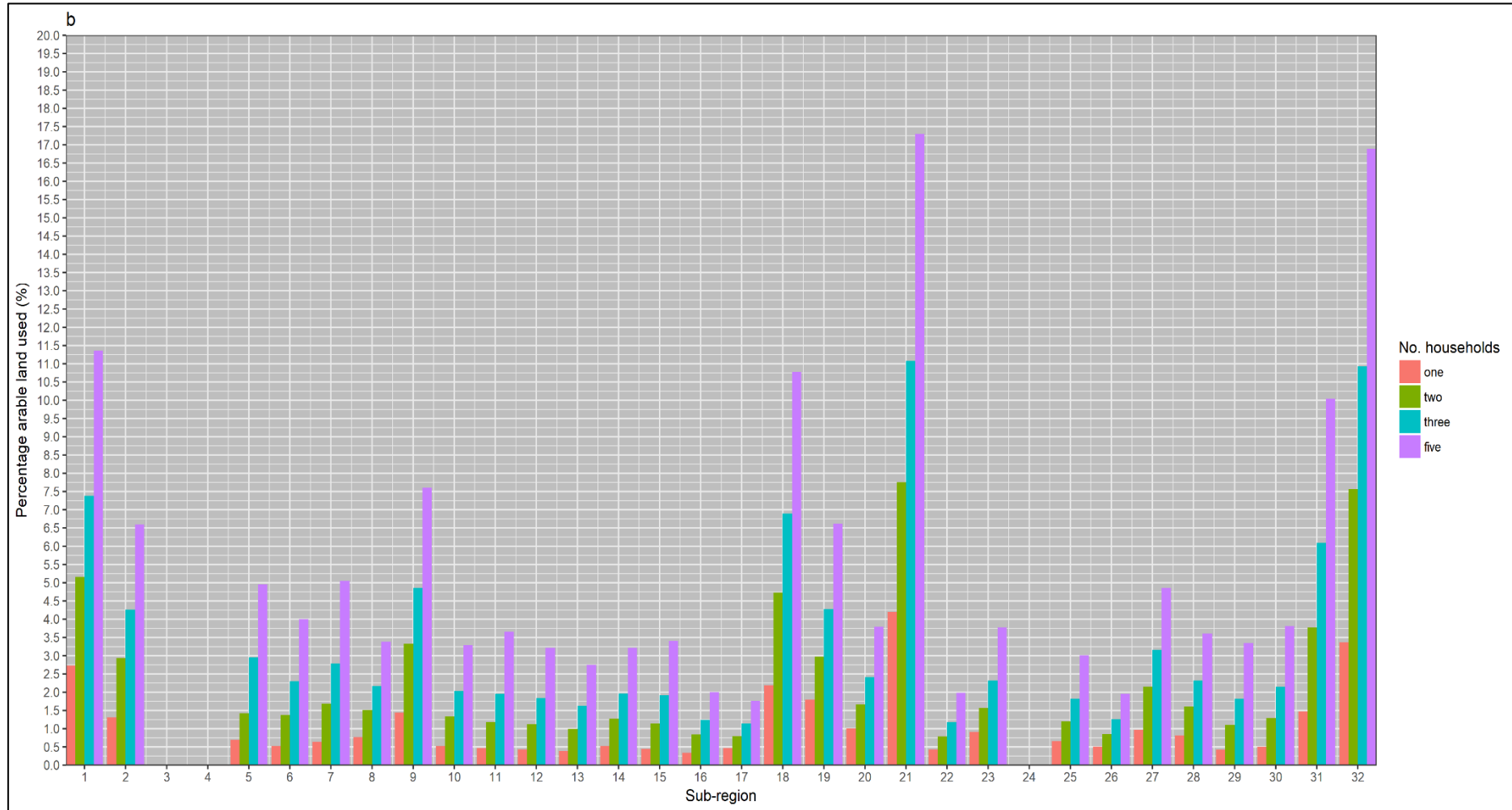


Figure 7.3b. Percentage of total available arable land used each year by settlements of different sizes undertaking arable intensification per sub-region using reconstructed settlement densities from the Early Roman Period A (12BCE-25CE).

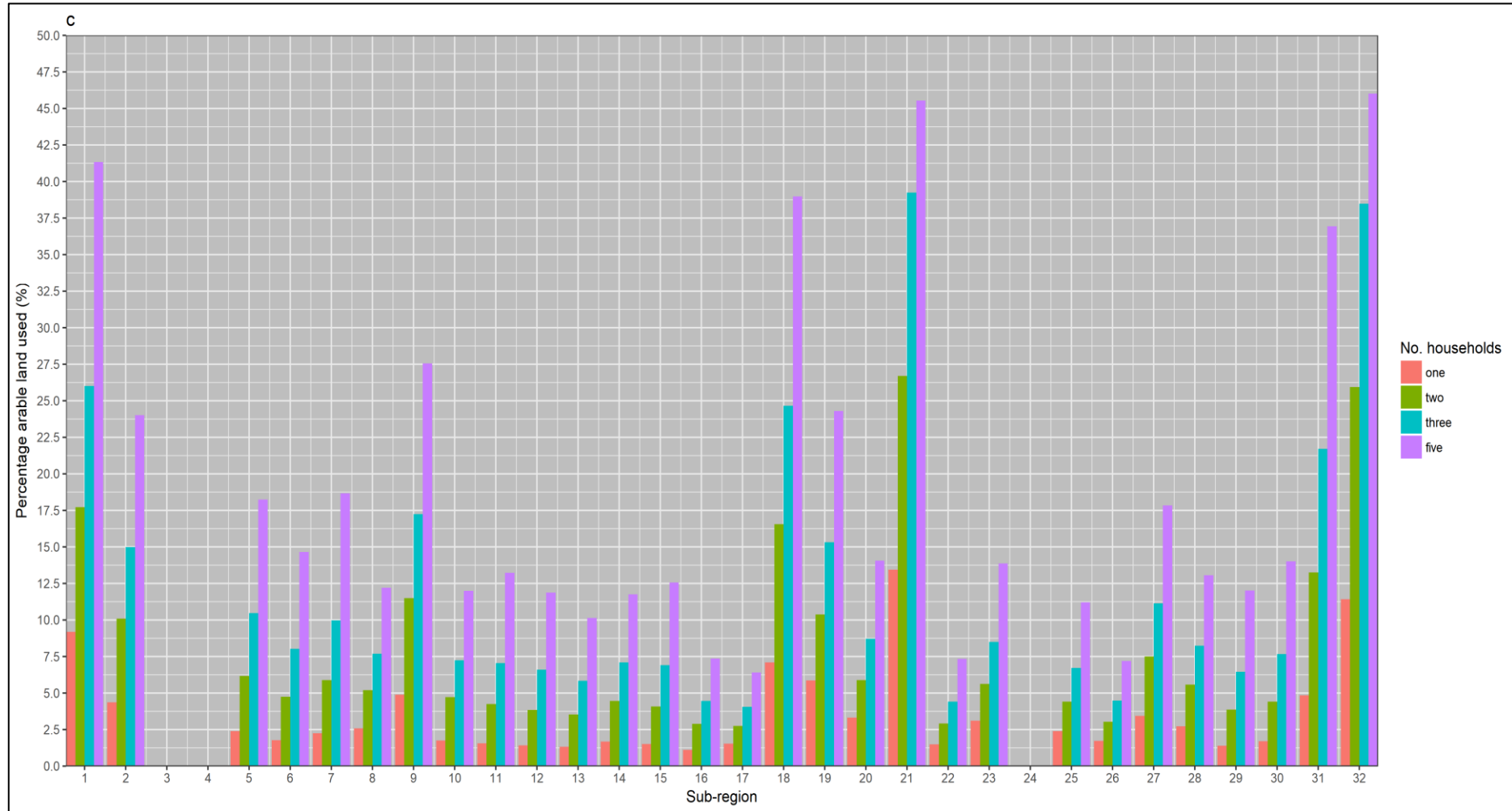


Figure 7.3c. Percentage of total available arable land used each year by settlements of different sizes undertaking arable extensification per sub-region using reconstructed settlement densities from the Early Roman Period A (12BCE-25CE).

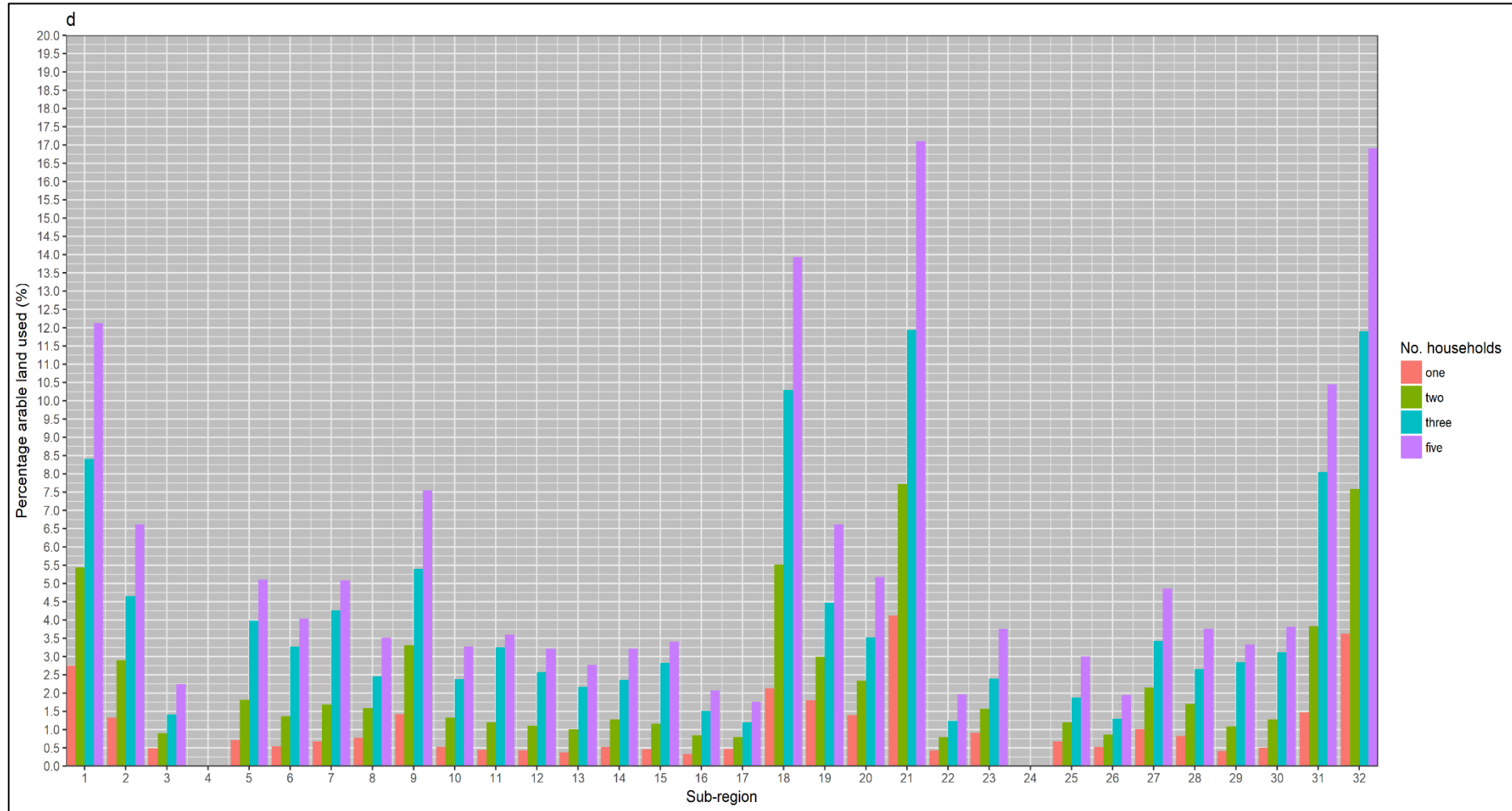


Figure 7.3d. Percentage of total available arable land used each year by settlements of different sizes undertaking arable intensification per sub-region using reconstructed settlement densities from the Early Roman Period B (25CE-70CE).

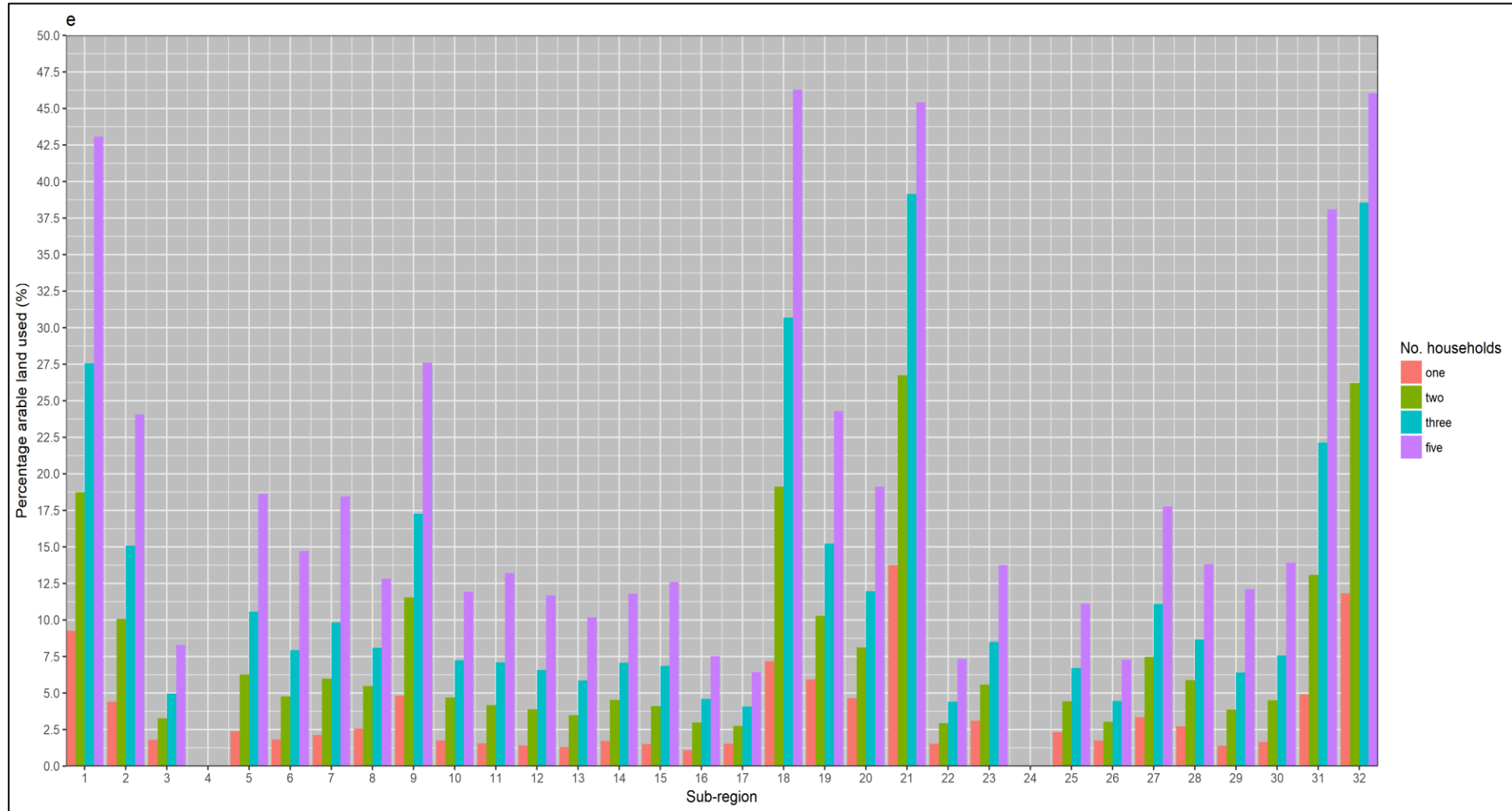


Figure 7.3e. Percentage of total available arable land used each year by settlements of different sizes undertaking arable extensification per sub-region using reconstructed settlement densities from the Early Roman Period B (25CE-70CE).

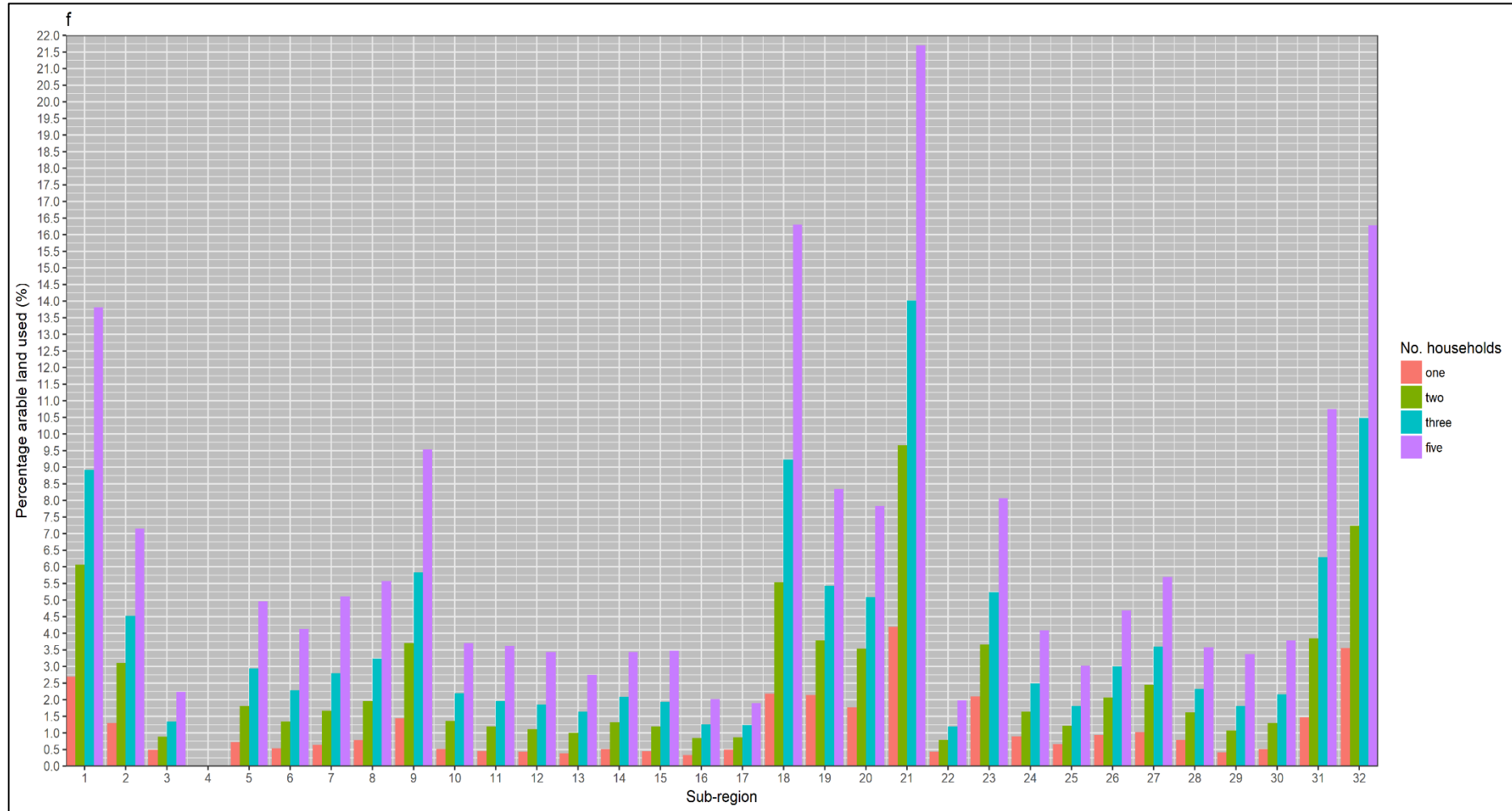


Figure 7.3f. Percentage of total available arable land used each year by settlements of different sizes undertaking arable intensification per sub-region using reconstructed settlement densities from the Middle Roman Period A (70CE-150CE).

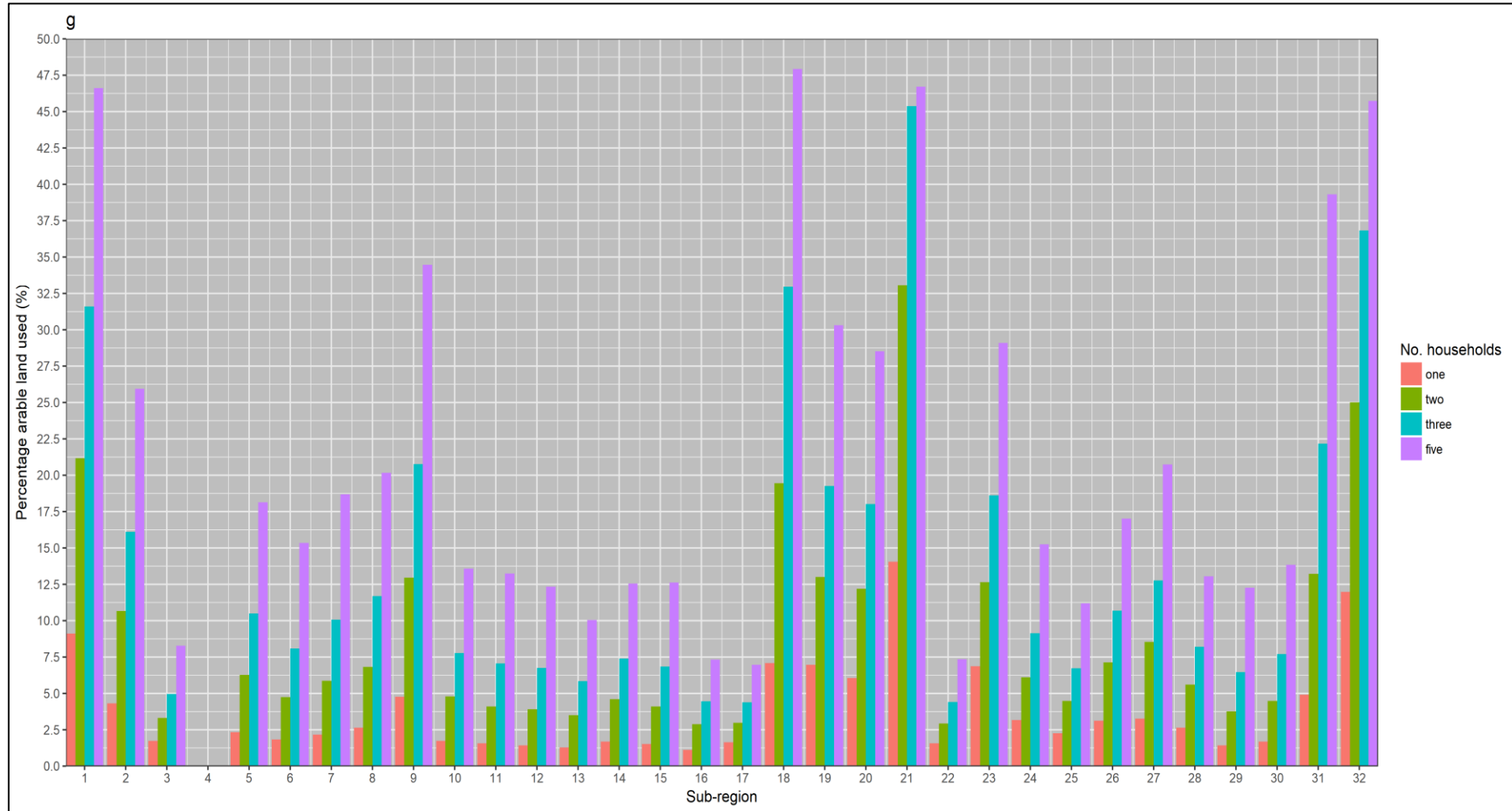


Figure 7.3g. Percentage of total available arable land used each year by settlements of different sizes undertaking arable extensification per sub-region using reconstructed settlement densities from the Middle Roman Period A (70CE-150CE).

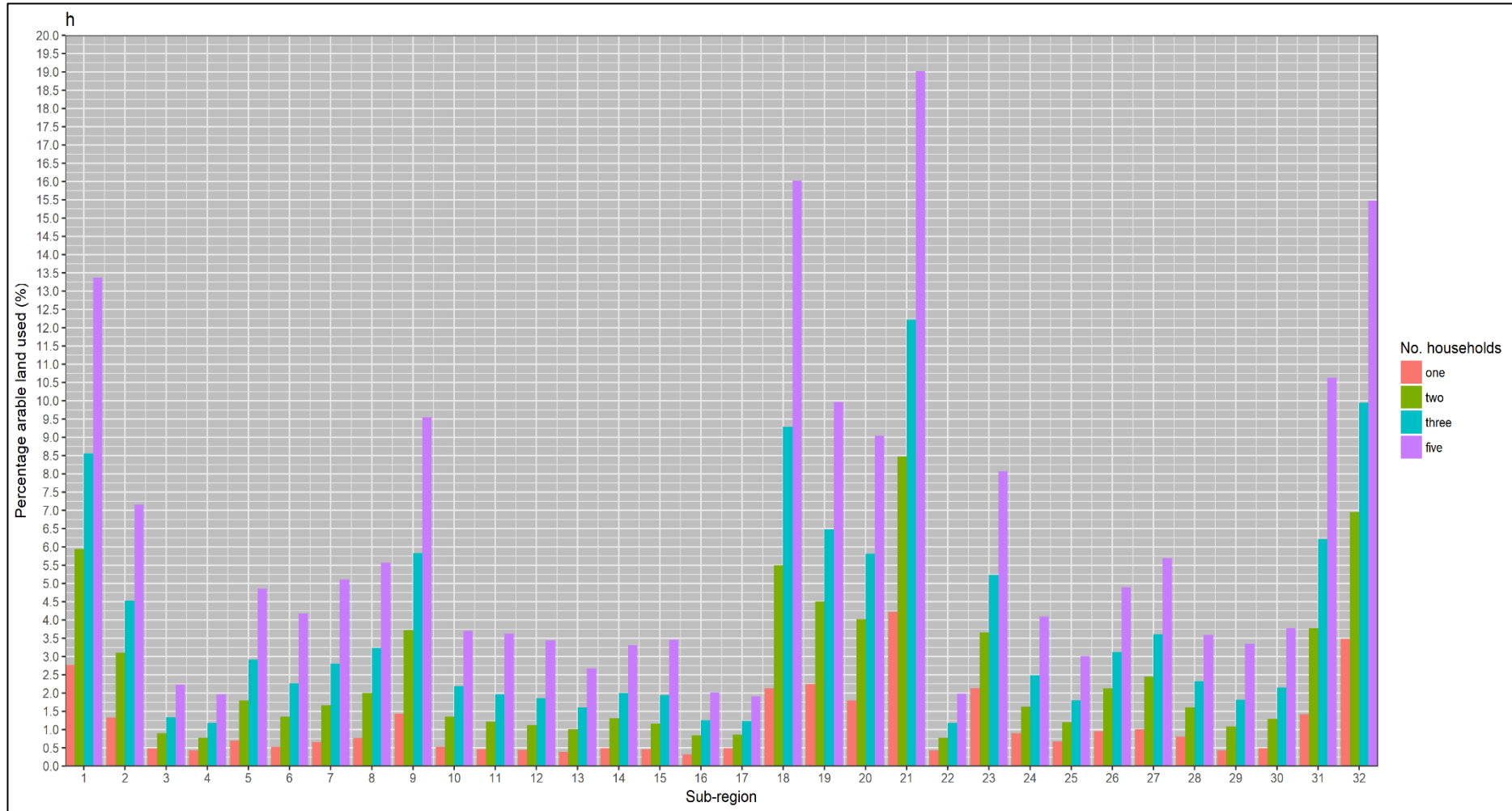


Figure 7.3h. Percentage of total available arable land used each year by settlements of different sizes undertaking arable intensification per sub-region using reconstructed settlement densities from the Middle Roman Period B (150CE-270CE).

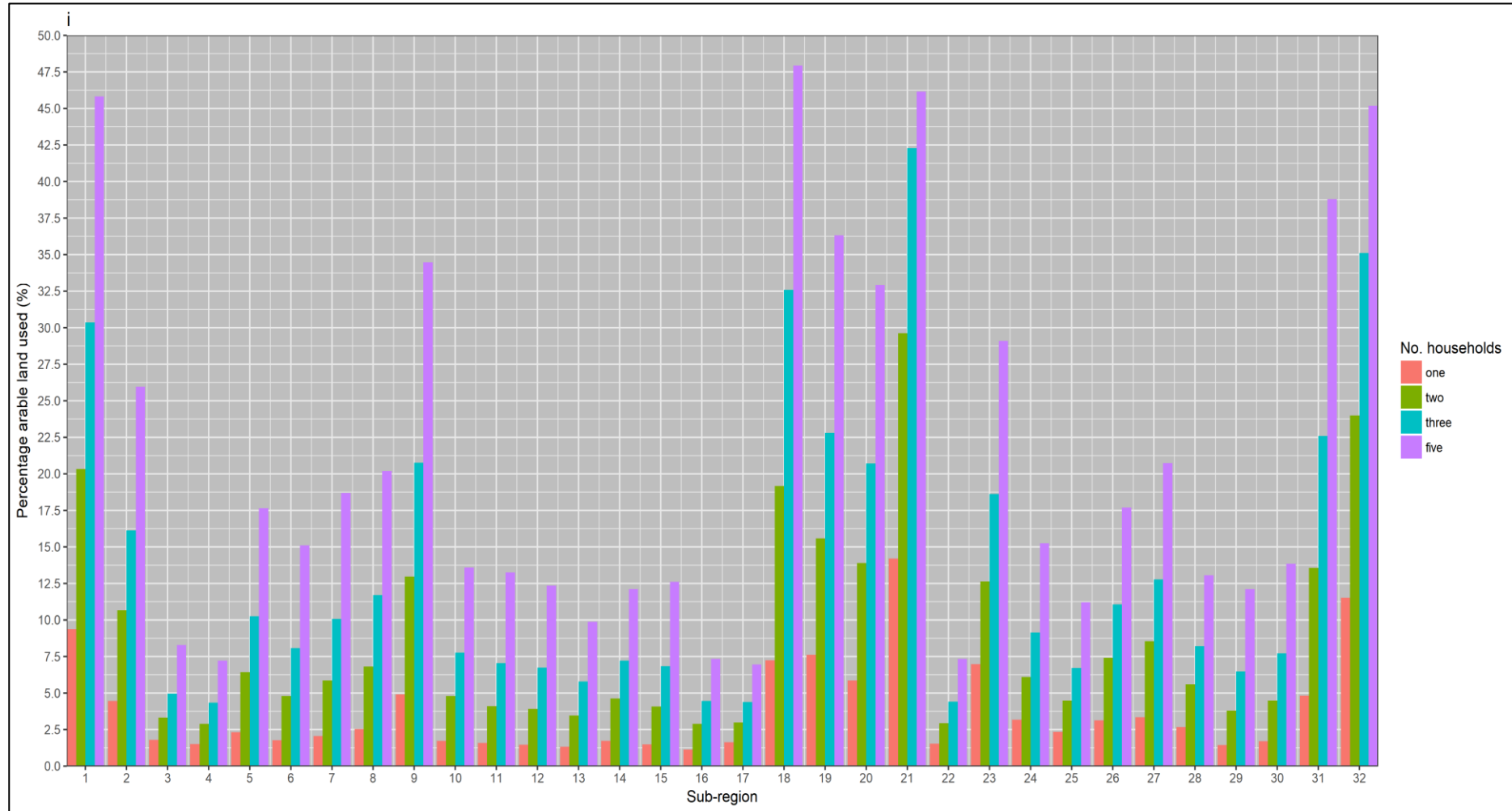


Figure 7.3i. Percentage of total available arable land used each year by settlements of different sizes undertaking arable extensification per sub-region using reconstructed settlement densities from the Middle Roman Period B (150CE-270CE).

7.2.2.1. Pasture and meadow land use in the Dutch *limes* zone

As with arable farming, animal husbandry in the Late Iron Age is assumed to have been subsistence-based with animal herds managed to produce sufficient meat and milk to fulfil the proportion of the calories required by the inhabitants of each settlement not met by grain. For settlements in the Late Iron Age, zooarchaeological evidence indicates cattle and sheep were managed for meat and milk. Cattle may have also been wealth indicators and used as a payment (Roymans 1996). In an analysis of subsistence-based agriculture, meat and milk available from a single simulated cattle herd managed for meat or milk were sufficient for settlements of all sizes when a majority (67.5%) of the total calories required came from grain (see chapter 5 section 5.3.1.3). The land used by settlements in the Late Iron Age for grazing and fodder collection is therefore a direct function of the mean total number of settlements per sub-region occupied in this period and the land required per cattle herd, which, for this period, is calculated as the mean of the land required by herds exploited for either meat or milk (29.25ha). In most sub-regions, the area of flood basin is sufficient to allow all settlements to manage the equivalent number of animals as one simulated herd. Sub-regions in the eastern part of the study region comprise very little flood basin and are covered mostly by High Pleistocene sands, cover sands, fluvial terraces and levees. As a result, the area of flood basin in these sub-regions is insufficient for the herds kept by all settlements occupying the region. However, according to the land suitability for agricultural activities proposed by de Kleijn *et al.* (2016, table A2), other landscape elements located in those sub-regions are equally as suitable for pasture and meadow land. Thus, in sub-regions 12, 15, 17, 29, 30 and 31, whilst the area of flood basin is insufficient in some scenarios, the area of other landscape elements also suitable for animal husbandry are sufficient to prevent settlements experiencing a shortage of pasture or meadow land. Settlements undertaking subsistence-based animal husbandry are not limited by the availability of suitable land, therefore. It was discussed previously (see chapter 5 section 5.3.2) that settlements were also not limited by labour within animal husbandry, with settlements of all sizes able to keep more animals than are needed for their own consumption requirements (see tables 7.4 & 7.5). The results show that neither the availability of land nor the availability of labour prevented settlements from producing sufficient meat and milk for their own needs under subsistence-based animal husbandry. Instead, biological factors such as fecundity of animals and natural mortality, and the exploitation strategy carried out by settlements have a greater impact on whether settlements can successfully produce sufficient meat and milk for their own consumption.

In the Early and Middle Roman periods, settlements in ROMFARMS engage in some form of surplus agricultural production. In addition to, or instead of, surplus production of grain, settlements in the Dutch *limes* zone may have engaged in the surplus production of animal products, or the animals themselves in the case of horse breeding. Analysis of the product output of cattle and sheep herds in hypothetical landscapes already indicated that settlements undertaking surplus production of animal products would need to keep more animals than are in a single herd as simulated in ROMFARMS. Whilst settlements are not restricted by labour to keeping the equivalent number of animals in one simulated herd of animals, land costs increase as more animals are kept. Accordingly, the total number of extra animals that settlements can manage is limited by either the total area of suitable pasture and meadow land or the labour pool of each settlement, whichever is lower. This assumes of course that settlements undertaking surplus animal husbandry will keep the maximum number of animals possible. To gauge whether the availability of land limits surplus animal husbandry in the sub-regions, the total number of extra animals that the available land can support can be compared with the total that settlements can manage. The total number of animals per settlement that can be supported by available land is calculated as:

$$t = \frac{\left(\frac{a_1}{a_2}\right)}{n},$$

where a_1 is the total area of available pasture and meadow land in each sub-region, a_2 is the total area of pasture and meadow land required by a single herd of animals (see section 5.3.2.1 chapter 5) and n is the median number of settlements occupying a sub-region.

The value for t is therefore the total number of animals that each settlement can manage based on available land if pasture and meadow land is divided equally among all settlements located in a sub-region. If the value for t is greater than the maximum number of animals that settlements can manage as limited by each settlement's labour pool, labour availability is more limiting than land availability. If the value for t is lower, then it can be assumed that land availability is most limiting. The values for t calculated in each period for landscapes occupied by different sized settlements are provided in tables 7.4 & 7.5. As extensive sheep husbandry as a form of surplus production was unlikely because of the large numbers of animals that would need to be kept, the calculations of maximum capacity are based on simulated herds of cattle only.

Given that land use for animal husbandry is a function of the land required by animal herds and the total number of settlements, there are uncertainties regarding how representative the results are of the situation in the Dutch *limes* zone in the past. Low-resolution of settlement dating and uncertainties of the number of settlements per sub-region already produce an incomplete data-set. Furthermore, the simplistic rules that control the creation and end of settlements in the simulation as well as the use of settlement density in place of absolute settlement numbers mean that the simulated median total number of settlements in each sub-region is unlikely to reflect the actual historical conditions. In addition, settlement occupation of sub-regions is simulated as homogeneous whereby landscapes are occupied only by settlements with the same number of households- a particularly unrealistic scenario. A further reason why the simulated results may not be representative is owing to the simulation of animal herds in ROMFARMS. Only three exploitation strategies are simulated whereas very many are possible. Therefore, the results are from only a limited number of possible scenarios. However, the results do provide good indications of where and when land availability may have restricted settlements.

From the results, a general observation can be made that small settlements comprising a single household are more limited by the availability of labour in a vast majority of sub-regions. Only in two to three sub-regions is the availability of land too low to allow settlements to manage as many animals as their labour pool will permit. In all other sub-regions, there is more land than settlements require. For larger settlements, the results are more mixed. In scenarios where settlements with two households occupy sub-regions, labour is the most limiting factor in a slight majority of sub-regions in the Early Roman period where the area of suitable land for surplus animal husbandry is more than can be used by settlements. In the Middle Roman period, the availability of land becomes more limiting in a small majority of sub-regions owing to an increase of settlement density in most sub-regions between the two periods. Settlements with two households located in the north-western peat region (sub-regions 2-4) and in the eastern part of the study region are more limited by the availability of land than labour in both the Early and Middle Roman periods. The comparatively smaller areas of suitable pasture and meadow land restrict the maximum number of animals each settlement can manage to a number below the maximum number that can be managed with available labour. The availability of land is also limiting in sub-regions 5-7. This is despite the relatively large area of suitable pasture and meadow land, in this case flood basin, in these sub-regions compared with other land types. For these sub-regions, the higher settlement density results in less land available to each settlement.

The results from these scenarios indicate possible sub-regions where inter-settlement competition for resources may have affected surplus animal husbandry.

The size of the labour pool available to settlements possessing three households is larger than available to smaller settlements with one or two households. In the majority of sub-regions in both the Early and Middle Roman Periods therefore, the area of suitable land for pasture or meadow land is insufficient for all settlements to manage the maximum number of animals that available labour will allow. Only in sub-regions with relatively very large areas of suitable land or sub-regions with low settlement density is the availability of labour more limiting than land availability. In scenarios with settlements with three households, sub-regions located in the central region (sub-regions 7-11, 27 & 28) comprise more land for animal husbandry than can be used by the labour pool available to settlements. Similarly, in the eastern part of the study region (e.g. sub-region 32) labour availability is more limiting owing to the large areas of potentially suitable pasture and meadow land. In some sub-regions (e.g. sub-regions 3 & 4), the availability of labour is more limiting for settlements despite comparatively smaller areas of suitable land for animal husbandry. However, in these sub-regions, the settlement density is low and there is thus little competition for land among settlements. The labour pool for settlements with five households is larger still and in all but a few sub-regions, the available land is insufficient for all settlements to keep the maximum number of animals that can be managed with available labour. Only in sub-regions with very low settlement densities is there more potential pasture and meadow land than the settlements require.

Chapter 7. Possibilities and limitations in reconstructed landscapes

PERIOD	NO. HOUSEHOLDS															
	ONE				TWO				THREE				FIVE			
REGION	ROMVA	ROMVB	ROMMA	ROMMB	ROMVA	ROMVB	ROMMA	ROMMB	ROMVA	ROMVB	ROMMA	ROMMB	ROMVA	ROMVB	ROMMA	ROMMB
1	9.19	9.19	9.19	9.19	7.35	6.89	6.13	6.49	7.35	6.89	5.80	6.13	7.35	6.89	5.80	6.13
2	4.10	4.10	4.10	4.10	2.73	2.73	2.46	2.46	2.59	2.59	2.34	2.34	2.59	2.59	2.34	2.34
3	-	13.15	13.15	13.15	-	9.86	9.86	9.86	-	9.86	9.86	9.86	-	9.86	9.86	9.86
4	-	-	-	18.87	-	-	-	14.16	-	-	-	14.16	-	-	-	14.16
5	7.28	7.94	7.94	7.28	3.80	3.64	3.80	3.64	2.91	2.82	2.91	3.01	2.73	2.57	2.73	2.91
6	7.67	7.67	7.67	7.67	4.00	4.00	4.00	3.83	2.97	2.97	2.88	2.88	2.42	2.42	2.09	2.14
7	9.71	10.59	10.59	9.71	4.85	4.85	5.06	5.06	3.76	3.76	3.64	3.64	2.77	2.77	2.65	2.65
8	11.52	10.56	5.76	10.56	7.92	7.92	5.51	5.51	7.92	7.92	4.09	4.09	7.92	7.92	3.84	3.84
9	14.43	14.43	15.74	14.43	9.11	9.11	7.53	7.53	8.66	8.66	6.41	6.41	8.66	8.66	6.18	6.18
10	7.83	7.83	7.83	7.83	4.09	4.09	3.92	3.92	3.92	3.92	3.24	3.24	3.76	3.76	3.03	3.03
11	6.49	6.49	6.49	6.49	3.25	3.25	3.39	3.39	2.43	2.43	2.43	2.43	1.81	1.81	1.81	1.81
12	5.48	5.48	5.48	5.48	2.86	2.86	2.74	2.74	2.06	2.06	2.06	2.06	1.83	1.83	1.53	1.53
13	4.12	4.49	4.49	4.12	2.06	2.15	2.06	2.15	1.65	1.59	1.65	1.65	1.54	1.50	1.54	1.59
14	7.47	7.47	7.47	7.47	3.90	3.90	3.73	3.73	3.58	3.58	3.20	3.45	3.45	3.45	3.09	3.32
15	6.40	6.40	6.40	6.98	3.20	3.20	3.20	3.20	2.40	2.40	2.48	2.40	1.97	1.97	1.87	1.87
16	2.09	2.09	2.09	2.09	1.14	1.09	1.14	1.14	1.05	1.01	1.05	1.05	1.05	1.01	1.05	1.05
17	10.37	10.37	10.37	10.37	9.43	9.43	8.64	8.64	9.43	9.43	8.64	8.64	9.43	9.43	8.64	8.64
18	12.57	12.57	12.57	12.57	8.38	8.38	6.29	6.56	7.94	5.80	4.71	4.87	7.94	5.59	3.87	4.08
19	11.63	11.63	11.63	9.52	10.47	10.47	8.05	6.54	10.47	10.47	8.05	6.54	10.47	10.47	8.05	6.54
20	15.58	10.39	10.39	8.50	13.35	9.35	5.84	5.19	13.35	9.35	5.84	4.92	13.35	9.35	5.84	4.92
21	8.62	7.90	7.90	8.62	6.32	6.32	4.99	5.58	6.32	6.32	4.74	5.58	6.32	6.32	4.74	5.58
22	30.80	30.80	30.80	30.80	23.10	23.10	23.10	23.10	23.10	23.10	23.10	23.10	23.10	23.10	23.10	23.10
23	27.40	27.40	27.40	10.96	21.92	21.92	9.13	9.13	21.92	21.92	9.13	9.13	21.92	21.92	9.13	9.13
24	-	-	24.03	24.03	-	-	18.03	18.03	-	-	18.03	18.03	-	-	18.03	18.03
25	32.92	32.92	32.92	32.92	24.69	24.69	24.69	24.69	24.69	24.69	24.69	24.69	24.69	24.69	24.69	24.69
26	16.51	16.51	16.51	9.01	14.15	14.15	5.50	5.21	14.15	14.15	5.21	4.95	14.15	14.15	5.21	4.95
27	11.83	11.83	11.83	11.83	8.35	8.35	6.76	6.76	7.89	7.89	6.45	6.45	7.89	7.89	6.45	6.45

28	11.10	11.10	11.10	12.11	8.32	7.83	8.32	66.59	8.32	7.83	8.32	8.32	8.32	7.83	8.32	8.32
29	5.15	5.15	5.15	5.15	2.57	2.57	2.68	2.68	1.99	1.93	1.99	1.93	1.44	1.40	1.40	1.44
30	7.15	7.15	7.15	7.15	3.73	3.73	3.73	3.73	2.68	2.68	2.68	2.68	2.20	2.20	2.26	2.26
31	14.15	14.15	14.15	15.44	7.08	7.08	7.38	7.08	5.86	5.66	5.48	5.31	5.66	5.31	5.00	5.00
32	17.44	15.99	15.99	15.99	11.29	11.29	11.29	11.99	10.66	10.66	11.29	11.99	10.66	10.66	11.29	11.99

Table 7.4. Maximum number of simulated cattle herds exploited for meat that can be managed by settlements of different sizes in each period and sub-region. Maximum number capped by availability of labour (red fill); maximum number capped by availability of pasture & meadow land located in floodbasins (green fill).

PERIOD REGION	NO. HOUSEHOLDS															
	ONE				TWO				THREE				FIVE			
	ROMVA	ROMVB	ROMMA	ROMMB	ROMVA	ROMVB	ROMMA	ROMMB	ROMVA	ROMVB	ROMMA	ROMMB	ROMVA	ROMVB	ROMMA	ROMMB
1	10.65	10.65	10.65	10.65	8.52	7.98	7.10	7.51	8.52	7.98	6.72	7.10	8.52	7.98	6.72	7.10
2	4.74	4.74	4.74	4.74	3.16	3.16	2.85	2.85	3.00	3.00	2.71	2.71	3.00	3.00	2.71	2.71
3	-	15.24	15.24	15.24	-	11.43	11.43	11.43	-	11.43	11.43	11.43	-	11.43	11.43	11.43
4	-	-	-	21.87	-	-	-	16.40	-	-	-	16.40	-	-	-	16.40
5	8.43	9.20	9.20	8.43	4.40	4.22	4.40	4.22	3.37	3.27	3.37	3.49	3.16	2.98	3.16	3.37
6	8.88	8.88	8.88	8.88	4.64	4.64	4.64	4.44	3.44	3.44	3.33	3.33	2.81	2.81	2.42	2.48
7	11.25	12.27	12.27	11.25	5.62	5.62	5.87	5.87	4.35	4.35	4.22	4.22	3.21	3.21	3.07	3.07
8	13.35	12.24	6.67	12.24	9.18	9.18	6.38	6.38	9.18	9.18	4.74	4.74	9.18	9.18	4.45	4.45
9	16.72	16.72	18.24	16.72	10.56	10.56	8.72	8.72	10.03	10.03	7.43	7.43	10.03	10.03	7.16	7.16
10	9.07	9.07	9.07	9.07	4.73	4.73	4.54	4.54	4.54	4.54	3.75	3.75	4.36	4.36	3.51	3.51
11	7.52	7.52	7.52	7.52	3.76	3.76	3.92	3.92	2.82	2.82	2.82	2.82	2.10	2.10	2.10	2.10
12	6.35	6.35	6.35	6.35	3.31	3.31	3.18	3.18	2.38	2.38	2.38	2.38	2.12	2.12	1.77	1.77
13	4.77	5.21	5.21	4.77	2.39	2.49	2.39	2.49	1.91	1.85	1.91	1.91	1.79	1.74	1.79	1.85
14	8.65	8.65	8.65	8.65	4.51	4.51	4.33	4.33	4.15	4.15	3.71	3.99	3.99	3.99	3.58	3.84
15	7.42	7.42	7.42	8.09	3.71	3.71	3.71	3.71	2.78	2.78	2.87	2.78	2.28	2.28	2.17	2.17
16	2.43	2.43	2.43	2.43	1.32	1.27	1.32	1.32	1.21	1.16	1.21	1.21	1.21	1.16	1.21	1.21
17	12.02	12.02	12.02	12.02	10.93	10.93	10.02	10.02	10.93	10.93	10.02	10.02	10.93	10.93	10.02	10.02

18	14.57	14.57	14.57	14.57	9.71	9.71	7.28	7.60	9.20	6.72	5.46	5.64	9.20	6.47	4.48	4.72
19	13.48	13.48	13.48	11.03	12.13	12.13	9.33	7.58	12.13	12.13	9.33	7.58	12.13	12.13	9.33	7.58
20	18.05	12.03	12.03	9.85	15.47	10.83	6.77	6.02	15.47	10.83	6.77	5.70	15.47	10.83	6.77	5.70
21	9.99	9.15	9.15	9.99	7.32	7.32	5.78	6.46	7.32	7.32	5.49	6.46	7.32	7.32	5.49	6.46
22	35.68	35.68	35.68	35.68	26.76	26.76	26.76	26.76	26.76	26.76	26.76	26.76	26.76	26.76	26.76	26.76
23	31.75	31.75	31.75	12.70	25.40	25.40	10.58	10.58	25.40	25.40	10.58	10.58	25.40	25.40	10.58	10.58
24	-	-	27.85	27.85	-	-	20.89	20.89	-	-	20.89	20.89	-	-	20.89	20.89
25	38.14	38.14	38.14	38.14	28.61	28.61	28.61	28.61	28.61	28.61	28.61	28.61	28.61	28.61	28.61	28.61
26	19.13	19.13	19.13	10.44	16.40	16.40	6.38	6.04	16.40	16.40	6.04	5.74	16.40	16.40	6.04	5.74
27	13.71	13.71	13.71	13.71	9.67	9.67	7.83	7.83	9.14	9.14	7.48	7.48	9.14	9.14	7.48	7.48
28	12.86	12.86	12.86	14.03	9.64	9.08	9.64	77.16	9.64	9.08	9.64	9.64	9.64	9.08	9.64	9.64
29	5.96	5.96	5.96	5.96	2.98	2.98	3.11	3.11	2.31	2.24	2.31	2.24	1.66	1.63	1.63	1.66
30	8.29	8.29	8.29	8.29	4.33	4.33	4.33	4.33	3.11	3.11	3.11	3.11	2.55	2.55	2.62	2.62
31	16.40	16.40	16.40	17.89	8.20	8.20	8.56	8.20	6.79	6.56	6.35	6.15	6.56	6.15	5.79	5.79
32	20.21	18.52	18.52	18.52	13.08	13.08	13.08	13.89	12.35	12.35	13.08	13.89	12.35	12.35	13.08	13.89

Table 7.5. Maximum number of simulated cattle herds exploited for milk that can be managed by settlements of different sizes in each period and sub-region. Maximum number capped by availability of labour (red fill); maximum number capped by availability of pasture & meadow land located in flood-basins (green fill).

The results also indicate little change over time. Changes in settlement density from the Early and Middle Roman Periods, as well as changes within periods from the sub-period A to B, have little impact on the overall pattern of potential land use by settlements undertaking surplus animal husbandry. A greater difference can be observed between scenarios where settlements exploit herds for meat or milk. Owing to the larger herd size of animals exploited for milk, the area of meadow and pasture land and the amount of labour required is higher. This has a greater impact on whether the availability of labour is a more limiting factor. There are thus more sub-regions where the number of animals that can be managed with available labour for each settlement is lower than the number that available land can support. A possible alternative strategy of surplus production that is simulated in ROMFARMS is intensification of arable farming. Zooarchaeological evidence from some settlements have indicated the management of cattle herds as auxiliary to arable intensification by providing traction and manure. Settlements undertaking intensification are therefore potentially limited not only by the availability of suitable arable land but also the availability of suitable land for animal husbandry. Without enough land to support sufficient numbers of animals to produce manure, settlements are unable to produce any more surplus grain than they would under subsistence-based farming. This is because settlements undertaking arable intensification rely solely on the yield-boosting effects of incorporating manure into arable land and do not cultivate any extra land than they would under a subsistence-based arable farming strategy. Small settlements with one or two households can derive enough manure from a single modelled cattle herd exploited for manure to incorporate 10t/ha arable land which is the assumed optimum rate. Larger settlements must keep the equivalent number of animals of two simulated herds to derive sufficient manure however there is a large enough labour pool to manage extra animals. In all periods and in all sub-regions, the area of land that can be potentially used for both pasture and meadow land for the number of animals in one to two modelled herds of cattle managed for manure is sufficient for all settlements occupying the sub-region. The results indicate therefore that settlements undertaking animal husbandry as an adjunct to arable intensification are restricted neither by labour nor by availability of land. Arable intensification in the sub-regions is therefore most limited by the manure output of the herd. The availability of manure is directly linked to the management strategy of cattle, with only three possible strategies simulated by ROMFARMS. Whilst manure is readily available from herds as simulated in ROMFARMS, alternative management strategies that are not simulated could restrict the availability of manure for settlements.

The availability of land for animal husbandry is not limiting in scenarios where settlements manage only small numbers of cattle either to provide sufficient milk and meat for the inhabitants of settlements or, in addition, to supply sufficient manure to undertake arable intensification. In some sub-regions, particularly those with high settlement density or relatively small areas of suitable land for animal husbandry or both, settlements are limited by the availability of land. Assuming that settlements undertaking extensive animal husbandry as a form of surplus agricultural production will aim to keep as many animals as possible restricted by land or labour (whichever is lowest), in some scenarios the area of suitable land in some sub-regions supports fewer animals than can be managed by larger settlements' labour pools. In other scenarios, the area of land supports more animals than the settlements can manage with available labour. Although both the availability of labour and land can be limiting factors in surplus animal husbandry, this does not mean that settlements are unable to keep extra animals.

7.3. Competition for land

The results have shown that for modelled subsistence-based and surplus strategies of arable farming and animal husbandry, settlements are not restricted by the availability of suitable land. Farming in ROMFARMS is simulated as an economically rational activity and therefore do not take

into account social variables such as communal land use, property rights and land ownership. These social variables would have impacted the availability of land. The more limiting factors are the availability of labour, sowing seed and manure. For the majority of scenarios there is sufficient land for each task of the agricultural economy: arable farming and animal husbandry. In some sub-regions however, the availability of all suitable pasture and meadow land is insufficient for settlements to manage as many animals as the available labour pool will permit i.e. surplus extensive animal husbandry. Adjusting calculations to include areas of landscape elements such as levees and stream-ridges that are suitable for both arable farming and animal husbandry could indicate where competition for land among tasks of the agricultural economy occurs. If settlements also use levees and stream-ridges for animal husbandry, labour then becomes the most limiting factor for settlements with one or two households in all but one sub-regions in all periods. There is sufficient arable land for settlements with one or two households to practice simultaneously either arable extensification or subsistence-based farming and extensive animal husbandry. There is therefore no competition between arable farming and animal husbandry for potential arable land in these scenarios.

In landscapes occupied by larger settlements, the results do indicate scenarios where competition for land can occur (see tables 7.6 & 7.7). Once again, settlements can increase the number of animals they can manage by using potential arable land as pasture or meadow land. If settlements undertake arable intensification, an even greater area of potential arable land is left available for animal husbandry than left under extensification. Furthermore, if settlements do not undertake any form of arable farming and instead use all land for animal husbandry, even more animals can be supported. Although perhaps unrealistic in a historical situation, these scenarios indicate when competition for land between arable farming and animal husbandry can exist. In scenarios with settlements with three households, the number of sub-regions where the availability of land is the most limiting factor decrease when arable land is also used for animal husbandry. The number further decreases when settlements undertake no arable farming. As a direct result of undertaking arable farming in any form, settlements with three households in some sub-regions are most limited by the availability of land for animal husbandry. In addition, the results show that arable intensification causes less competition for land among agricultural tasks than arable extensification.

Conversely, when sub-regions are occupied by settlements with five households, the inclusion of potential arable land such as levees and stream-ridges as potential pasture and meadow land has little effect. The number of sub-regions where the availability of land is most limiting for animal husbandry does not change significantly between scenarios where potential arable land is not used and scenarios where it is used. The total number of animals that can be supported by available land can indeed be increased when settlements use potential arable land. However, the constraints of the natural landscape remain more limiting than the conditions created by settlements undertaking arable farming.

Chapter 7. Possibilities and limitations in reconstructed landscapes

PERIOD REGION	NO. HOUSEHOLDS															
	ONE				TWO				THREE				FIVE			
	ROMVA	ROMVB	ROMMA	ROMMB	ROMVA	ROMVB	ROMMA	ROMMB	ROMVA	ROMVB	ROMMA	ROMMB	ROMVA	ROMVB	ROMMA	ROMMB
1	18.25	10.65	10.65	10.65	8.52	7.98	7.10	7.51	8.52	7.98	6.72	7.10	8.52	7.98	6.72	7.10
2	8.13	4.74	4.74	4.74	3.16	3.16	2.85	2.85	3.00	3.00	2.71	2.71	3.00	3.00	2.71	2.71
3	-	13.03	13.03	13.03	-	11.43	11.43	11.43	-	11.43	11.43	11.43	-	11.43	11.43	11.43
4	-	-	-	13.03	-	-	-	16.40	-	-	-	16.40	-	-	-	16.40
5	14.46	9.20	9.20	8.43	4.40	4.22	4.40	4.22	3.37	3.27	3.37	3.49	3.16	2.98	3.16	3.37
6	15.23	8.88	8.88	8.88	4.64	4.64	4.64	4.44	3.44	3.44	3.33	3.33	2.81	2.81	2.42	2.48
7	19.28	12.27	12.27	11.25	5.62	5.62	5.87	5.87	4.35	4.35	4.22	4.22	3.21	3.21	3.07	3.07
8	20.98	12.24	6.67	12.24	9.18	9.18	6.38	6.38	9.18	9.18	4.74	4.74	9.18	9.18	4.45	4.45
9	28.66	16.72	18.24	16.72	10.56	10.56	8.72	8.72	10.03	10.03	7.43	7.43	10.03	10.03	7.16	7.16
10	15.56	9.07	9.07	9.07	4.73	4.73	4.54	4.54	4.54	4.54	3.75	3.75	4.36	4.36	3.51	3.51
11	12.89	7.52	7.52	7.52	3.76	3.76	3.92	3.92	2.82	2.82	2.82	2.82	2.10	2.10	2.10	2.10
12	10.89	6.35	6.35	6.35	3.31	3.31	3.18	3.18	2.38	2.38	2.38	2.38	2.12	2.12	1.77	1.77
13	8.18	5.21	5.21	4.77	2.39	2.49	2.39	2.49	1.91	1.85	1.91	1.91	1.79	1.74	1.79	1.85
14	14.83	8.65	8.65	8.65	4.51	4.51	4.33	4.33	4.15	4.15	3.71	3.99	3.99	3.99	3.58	3.84
15	12.71	7.42	7.42	8.09	3.71	3.71	3.71	3.71	2.78	2.78	2.87	2.78	2.28	2.28	2.17	2.17
16	4.16	2.43	2.43	2.43	1.32	1.27	1.32	1.32	1.21	1.16	1.21	1.21	1.21	1.16	1.21	1.21
17	17.17	12.02	12.02	12.02	10.93	10.93	10.02	10.02	10.93	10.93	10.02	10.02	10.93	10.93	10.02	10.02
18	24.97	14.57	14.57	14.57	9.71	9.71	7.28	7.60	9.20	6.72	5.46	5.64	9.20	6.47	4.48	4.72
19	17.33	13.48	13.48	11.03	12.13	12.13	9.33	7.58	12.13	12.13	9.33	7.58	12.13	12.13	9.33	7.58
20	18.05	12.03	12.03	9.85	15.47	10.83	6.77	6.02	15.47	10.83	6.77	5.70	15.47	10.83	6.77	5.70
21	15.69	9.15	9.15	9.99	7.32	7.32	5.78	6.46	7.32	7.32	5.49	6.46	7.32	7.32	5.49	6.46
22	13.03	13.03	13.03	13.03	17.38	17.38	17.38	17.38	26.76	26.76	26.76	26.76	26.76	26.76	26.76	26.76
23	17.38	17.38	17.38	12.70	21.72	21.72	10.58	10.58	25.40	25.40	10.58	10.58	25.40	25.40	10.58	10.58
24	-	-	13.03	13.03	-	-	17.38	17.38	-	-	20.89	20.89	-	-	20.89	20.89
25	13.03	13.03	13.03	13.03	17.38	17.38	17.38	17.38	28.61	28.61	28.61	28.61	28.61	28.61	28.61	28.61
26	19.13	19.13	19.13	10.44	16.40	16.40	6.38	6.04	16.40	16.40	6.04	5.74	16.40	16.40	6.04	5.74
27	23.49	13.71	13.71	13.71	9.67	9.67	7.83	7.83	9.14	9.14	7.48	7.48	9.14	9.14	7.48	7.48

Chapter 7. Possibilities and limitations in reconstructed landscapes

28	22.05	12.86	12.86	14.03	9.64	9.08	9.64	12.86	9.64	9.08	9.64	9.64	9.64	9.08	9.64	9.64
29	10.22	5.96	5.96	5.96	2.98	2.98	3.11	3.11	2.31	2.24	2.31	2.24	1.66	1.63	1.63	1.66
30	14.21	8.29	8.29	8.29	4.33	4.33	4.33	4.33	3.11	3.11	3.11	3.11	2.55	2.55	2.62	2.62
31	28.11	16.40	16.40	17.89	8.20	8.20	8.56	8.20	6.79	6.56	6.35	6.15	6.56	6.15	5.79	5.79
32	30.41	18.52	18.52	18.52	13.08	13.08	13.08	13.89	12.35	12.35	13.08	13.89	12.35	12.35	13.08	13.89

Table 7.6. Maximum number of simulated cattle herds exploited for meat that can be managed by settlements of different sizes in each period and sub-region. Maximum number capped by availability of labour (red fill); maximum number capped by availability of pasture & meadow land located in all landscape elements (green fill).

PERIOD	NO. HOUSEHOLDS															
	ONE				TWO				THREE				FIVE			
REGION	ROMVA	ROMVB	ROMMA	ROMMB	ROMVA	ROMVB	ROMMA	ROMMB	ROMVA	ROMVB	ROMMA	ROMMB	ROMVA	ROMVB	ROMMA	ROMMB
1	15.75	9.19	9.19	9.19	7.35	6.89	6.13	6.49	7.35	6.89	5.80	6.13	7.35	6.89	5.80	6.13
2	7.02	4.10	4.10	4.10	2.73	2.73	2.46	2.46	2.59	2.59	2.34	2.34	2.59	2.59	2.34	2.34
3	-	10.84	10.84	10.84	-	9.86	9.86	9.86	-	9.86	9.86	9.86	-	9.86	9.86	9.86
4	-	-	-	10.84	-	-	-	14.16	-	-	-	14.16	-	-	-	14.16
5	12.48	7.94	7.94	7.28	3.80	3.64	3.80	3.64	2.91	2.82	2.91	3.01	2.73	2.57	2.73	2.91
6	13.14	7.67	7.67	7.67	4.00	4.00	4.00	3.83	2.97	2.97	2.88	2.88	2.42	2.42	2.09	2.14
7	16.64	10.59	10.59	9.71	4.85	4.85	5.06	5.06	3.76	3.76	3.64	3.64	2.77	2.77	2.65	2.65
8	18.10	10.56	5.76	10.56	7.92	7.92	5.51	5.51	7.92	7.92	4.09	4.09	7.92	7.92	3.84	3.84
9	24.73	14.43	15.74	14.43	9.11	9.11	7.53	7.53	8.66	8.66	6.41	6.41	8.66	8.66	6.18	6.18
10	13.43	7.83	7.83	7.83	4.09	4.09	3.92	3.92	3.92	3.92	3.24	3.24	3.76	3.76	3.03	3.03
11	11.13	6.49	6.49	6.49	3.25	3.25	3.39	3.39	2.43	2.43	2.43	2.43	1.81	1.81	1.81	1.81
12	9.40	5.48	5.48	5.48	2.86	2.86	2.74	2.74	2.06	2.06	2.06	2.06	1.83	1.83	1.53	1.53
13	7.06	4.49	4.49	4.12	2.06	2.15	2.06	2.15	1.65	1.59	1.65	1.65	1.54	1.50	1.54	1.59
14	12.80	7.47	7.47	7.47	3.90	3.90	3.73	3.73	3.58	3.58	3.20	3.45	3.45	3.45	3.09	3.32
15	10.97	6.40	6.40	6.98	3.20	3.20	3.20	3.20	2.40	2.40	2.48	2.40	1.97	1.97	1.87	1.87
16	3.59	2.09	2.09	2.09	1.14	1.09	1.14	1.14	1.05	1.01	1.05	1.05	1.05	1.01	1.05	1.05

Chapter 7. Possibilities and limitations in reconstructed landscapes

17	14.82	10.37	10.37	10.37	9.43	9.43	8.64	8.64	9.43	9.43	8.64	8.64	9.43	9.43	8.64	8.64
18	21.55	12.57	12.57	12.57	8.38	8.38	6.29	6.56	7.94	5.80	4.71	4.87	7.94	5.59	3.87	4.08
19	14.96	11.63	11.63	9.52	10.47	10.47	8.05	6.54	10.47	10.47	8.05	6.54	10.47	10.47	8.05	6.54
20	15.58	10.39	10.39	8.50	13.35	9.35	5.84	5.19	13.35	9.35	5.84	4.92	13.35	9.35	5.84	4.92
21	13.54	7.90	7.90	8.62	6.32	6.32	4.99	5.58	6.32	6.32	4.74	5.58	6.32	6.32	4.74	5.58
22	10.84	10.84	10.84	10.84	18.78	18.78	18.78	18.78	23.10	23.10	23.10	23.10	23.10	23.10	23.10	23.10
23	14.45	14.45	14.45	10.96	21.92	21.92	9.13	9.13	21.92	21.92	9.13	9.13	21.92	21.92	9.13	9.13
24	-	-	10.84	10.84	-	-	18.03	18.03	-	-	18.03	18.03	-	-	18.03	18.03
25	10.84	10.84	10.84	10.84	18.78	18.78	18.78	18.78	24.69	24.69	24.69	24.69	24.69	24.69	24.69	24.69
26	16.51	16.51	16.51	9.01	14.15	14.15	5.50	5.21	14.15	14.15	5.21	4.95	14.15	14.15	5.21	4.95
27	20.28	11.83	11.83	11.83	8.35	8.35	6.76	6.76	7.89	7.89	6.45	6.45	7.89	7.89	6.45	6.45
28	19.03	11.10	11.10	12.11	8.32	7.83	8.32	11.10	8.32	7.83	8.32	8.32	8.32	7.83	8.32	8.32
29	8.82	5.15	5.15	5.15	2.57	2.57	2.68	2.68	1.99	1.93	1.99	1.93	1.44	1.40	1.40	1.44
30	12.27	7.15	7.15	7.15	3.73	3.73	3.73	3.73	2.68	2.68	2.68	2.68	2.20	2.20	2.26	2.26
31	24.26	14.15	14.15	15.44	7.08	7.08	7.38	7.08	5.86	5.66	5.48	5.31	5.66	5.31	5.00	5.00
32	25.28	15.99	15.99	15.99	11.29	11.29	11.29	11.99	10.66	10.66	11.29	11.99	10.66	10.66	11.29	11.99

Table 7.7. Maximum number of simulated cattle herds exploited for milk that can be managed by settlements of different sizes in each period and sub-region. Maximum number capped by availability of labour (red fill); maximum number capped by availability of pasture & meadow land located in all landscape elements (green fill).

7.4. Grain supply and demand in sub-regions: quantities and mechanisms

The final objectives of this chapter concern surplus production of grain and animal products by rural settlements and how it compares with estimated consumer demand from military and civilian settlements in the reconstructed sub-regions and in the study region as a whole. These comparisons will help generate hypotheses regarding both the feasibility of local supply of grain, animal products (or both) to military and civilian settlements in general, and, if possible, the mechanisms with which local supply could be achieved.

7.4.1. Estimating demand from military and civilian settlements

Demand from settlements not producing their own food such as military settlements (*castella*, *castra* and 'mini-castella') and civilian settlements (*vici*) is determined by the population of these settlements, the proportion of the inhabitants' diet that is derived from grain or animal products, and the proportion of this requirement that was supplied by local settlements. The first step in estimating demand is therefore to estimate the number of inhabitants in each of the military and civilian settlements within the study region.

7.4.1.1. Estimating the military and civilian population

In light of the uncertainties in the data-set, it is unsurprising that estimating the number of inhabitants in the military and civilian settlements, and the total population in each sub-region, is not simple. Uncertainties regarding the existence of military and civilian settlements may lead to over- or under-estimation of the non-rural population in a sub-region, and uncertainties regarding dating of occupation could lead to over- or under-estimation of the non-rural population in a specific time period. Furthermore, there is no evidence to indicate consistent occupation within a time period, particularly in the military settlements. As there are only a few indications of the specific units occupying military settlements, and these indications largely date from a narrow time period after *castella* were reconstructed in stone and before the centralization of tile and brick manufacturing, it is not possible to accurately map temporal trends in occupation within time periods. Often, it can only be said that at some time within a time-period, a military unit was stationed in a military settlement. In addition, and perhaps most problematic, it is extremely difficult to estimate what a "normal" population of a military settlement was, therefore, even if uncertainties regarding the existence of certain settlements or dating could be correct, there would remain fundamental uncertainties regarding population size. Even less is known about civilian settlements such as *vici*. Accordingly, the estimates provided are very uncertain, and at times simply best guesses.

7.4.1.1.1. Estimating the military population

For some of the military settlements located in the sub-region, finds indicate the presence of named units.⁵ From these, estimates of the number of inhabitants can be made for specific periods at some sites. At other sites, however, there are no indications for the possible number of soldiers present. The inscriptions that do exist point to the presence of a *cohors quingenaria peditata* (an infantry cohort) in most *castella*, with some inscriptions evidencing the presence of a *cohors*

⁵ Some examples include: *cohors III Gallorum* (Bogaers 1972, fig. 31a-b), *cohors IV Thracum* (Bogaers 1974, pl. XXVI 3) at Valkenburg; *cohors XV Voluntariorum Civicum Romanum Pia Fidelis* (ILS 9178; see Alföldy 1968; Hübner 1885), *cohors I Lucensium* (CIL XIII 8823), *Numerus Exploratorum Batavorum* (ILS 9186) at Leiden-Roomburg; *cohors VI Breucorum* (AE 1975 0632= AE 1980 0657, AE 2000 1625a; see also Bogaers 1969 & 1980b; Haalebos 2000) at Alphen aan den Rijn; *cohors XV Voluntariorum* (AE 2001 1423e; see also Bogaers 1978, 601-602) at Woerden; *cohors II Hispanorum* (AE 1936 0089 = AE 1937 233 = AE 1936 0092) at Utrecht; *cohors II Brittonum* (Bogaers 1974, pl. XXVII 2), *ala I Thracum Victrix* (CIL XIII 8818; see Bogaers 1974, XXVI), *cohors I Flavia Hispanorum* (Bogaers 1974, p. XXVII 3) at Vechten; *cohors II Hispanorum* (AE 1975 639g), *cohors II Thracum* (AE 1975 639f) at Maurik; and *Legio X Gemina* (AE 1968 0404, AE 1979 0414, AE 1979 0415, AE 1977 0416, AE 1977 0542, AE 2009 925-928; see also Bogaers 1979; Willems & van Enckevort 2009). NB. This is not an exhaustive list of military inscriptions, tile stamps etc. found in the Dutch *limes* region.

quingenaria equitata (a mixed infantry and cavalry cohort) or *ala quingenaria* (a cavalry unit). This would indicate that during occupation of these military settlements, a population of between 480 and 600 soldiers can be expected when the *castella* were fully occupied following traditional estimates of cohort size (480 foot soldiers in either a *cohors quingenaria peditata* or *cohors quingenaria equitata* with an additional 120 cavalry men in the latter, see Goldsworthy 1996). The garrison at Vechten was assumed to be double-sized (Zandstra & Polak 2012) and at Nijmegen, after 70 CE, the Xth legion was garrisoned at the Hunerberg *castra* possessing c. 5500 men. Multiple estimates for the size of an Imperial legion exist have been cited by Roth (1994, 346) with the mean used in calculations. The legion was moved in 104 CE after which it is unknown how many soldiers remained in the much-reduced garrison. At the short-lived Early Roman *castra* at Hunerberg there was space for up to two legions (Willems & van Enckevort 2009). The number of soldiers stationed in the so-called 'mini-*castella*' is unknown. Whether the settlements at Valkenburg-Marktveld or Ockenburgh housed extra units or detachments from units stationed in larger *castella* nearby can not be said with any confidence and their populations are not included in calculations. Estimates are complicated further by suggestions that the size of cohorts occupying *castella* in the Dutch *limes* zone were not as large as traditional measurements. Van Dinter *et al.* (2013) assumed 350 soldiers per *castella* whereas Glasbergen & Groenman-van Waateringe (1974) assumed as few as 250 men. Without compelling evidence for population size where the name of the occupying military unit is not known from inscriptions or for the 'normal' size of the cohorts present, a range of values have been used: 250, 350 and 500 men per cohort (after Glasbergen & Groenman-van Waateringe 1974; van Dinter *et al.* 2014; and traditional estimates- see Willems 1986; Goldsworthy 1996, 22 table 2). The total population per sub-region and per period is provided in table 7.8. Due to the very speculative nature for any estimates of the population of 'mini-*castella*', they have been excluded from any calculations.

REGION	IJZL	ROMVA	ROMVB	ROMMA	ROMMB
1	0	0	500-1200	500-1200	500-1200
2	0	0	0	500-1200	500-1200
3	0	0	500-1200	500-1200	500-1200
4	0	0	250-600	250-600	250-600
5	0	0	250-600	250-600	250-600
6	0	500-1200 ^b	750-1800	750-1800 ^c	500-1200
7	0	0	0	0	0
8	0	0	0	0	0
9	0	0	0	0	0
10	0	0	250-600	500-1200	500-1200
11	0	0	0	0	0
12	0	0	250-600	250-600	250-600
13	0	0	0	0	0
14	0	250-600	250-600	250-600	250-600
15	0	0	0	0	0
16	0	0	250-600	250-600	250-600
17	11000 ^a	250-600	250-600	5500 ^d	0
18 ^e	0	0	0	0	0
19	0	0	0	0	0
20	0	0	0	0	0
21	0	0	0	0	0
22	0	0	0	0	0
23	0	0	0	0	0
24	0	0	0	0	0
25	0	0	0	0	0
26	0	0	0	0	0
27	0	0	0	0	0
28	0	0	0	0	0
29	0	0	0	0	0
30	0	0	0	0	0
31	0	0	0	0	0
32	0	0	0	0	0

Table 7.8. Estimated total military population per sub-region. ^a Possible population of two legions present in Nijmegen Hunerberg between 19-10 BCE. ^b Range is provided as three assumptions for cohort size are used: 250 (after Glasbergen & Groenman-van Waateringe 1974), 350 (after van Dinter et al. 2014) and 600 (traditional estimates of cohorts quingenaria equitata; see Goldsworthy 1996). ^c Castellum at Vechten is considered to have housed a double-sized cohort. ^d Possible population of one legion present in Nijmegen Hunerberg between after the Batavian revolt and 103/104 CE. ^e Sub-region 18 contains a mini-castellum whose population is not included in calculations given the severe uncertainties in estimating the number of inhabitants in these military installations.

SUB-REGION	ROMVA	ROMVB	ROMMA	ROMMB
1	0	0	250-600	500-1200
2	0	0	250-600	250-600
3	0	0	250-600	250-600
4	0	0	250-600	250-600
5	0	0	250-600	250-600
6	0	0	750-1800	750-1800
7	0	0	0	0
8	0	0	0	0
9	0	0	0	0
10	0	0	0	0
11	0	0	0	0
12	0	0	250-600	250-600
13	0	0	0	0
14	0	0	0	0
15	250-600 ^a	250-600	5000 ^d	5000
16	0	0	0	0
17	0	0	0	0
18	0	1000 ^b	1000	1000
19	0	0	0	0
20	0	0	0	0
21	0	0	0	0
22	0	0	0	0
23	0	0	0	0
24	0	0	0	0
25	0	0	0	0
26	0	0	0	0
27	0	0	0	0
28	0	0	500-1200	500-1200
29	0	0	0	0
30	0	0	0	0
31	0	0	0	0
32	0	250-600 ^c	250-600	250-600

Table 7.9. Estimated total population of towns and vici per sub-region. ^a Range is provided as three assumptions for cohort size are used: 250 (after Glasbergen & Groenman-van Waateringe 1974), 350 (after van Dinter et al. 2014) and 600 (traditional estimates of cohorts quingenaria equitata; see Goldsworthy 1996). ^b Estimated population of Forum Hadriani (Voorburg). ^c Estimated population of Cuijk. ^d Estimated population of Ulpia Noviomagus (Nijmegen Waterkwartier).

7.4.1.1.2. Estimating the civilian population

Very little is known about the occupation of civilian settlements such as towns and *vici*, in addition to those uncertainties regarding the existence of *vici* in some areas of the study region. Estimates of the civilian population in each sub-region are therefore even more uncertain than those of the military population. Van Dinter *et al.* (2013) estimated that the population of each *vicus* was equal

to the population of the associated *castella*. Their study region however did not include the much larger settlements at Nijmegen (Oppidum Batavorum/Ulpia Noviomagus), Voorburg (Forum Hadriani) and other *vici* identified by Roymans (2004) in the hinterland (e.g. Alem/Rossum and Kessel-Lith). Perhaps, the non-military population of Ulpia Noviomagus reached c. 5000 people (Willems 1990, 71). The population of Forum Hadriani may have reached 1000 people (Buijtendorp 2010, 71). These are, of course, very tentative estimates of populations at their height and do not take into account any fluctuation in size over time. Often these estimates amount to little more than “best guesses”. It is hoped, as van Dinter *et al.* (2013, 31) also believed, that, even if new evidence provides less uncertain estimates of population sizes in the *vici*, the order of magnitude of the estimated demand will remain the same. The estimated population of non-military and non-agrarian inhabitants of each sub-region is provided in table 7.9.

7.4.1.2. Estimating demand for grain and animal products

Calculating the total amount of food that military and civilian settlements required is determined by the estimates of population, which range, as discussed, from probable to very uncertain, and the calories required by each individual. A further adjustment can be made concerning the proportion of the total calories required that were supplied by local rural producer settlements. Estimating the required calories in military settlements is, however, more straightforward than for civilian settlements. Not only are the estimates for population size probably more representative of the actual situation in the past, it can also be assumed with some confidence that the population was homogeneous, comprising adult men of military age (c. 18-43; see Roth 1999, 10-11). It can be expected therefore that each soldier required approximately 3000kCal per day (Roth 1999, 12). The Roman military diet was probably predominantly comprised of grain with meat also consumed but to a lesser degree (Davies 1971). The ratio of grain to meat in the diet is unknown, however van Dinter *et al.* (2013) assumed 67.5% of the diet was grain-based. This would amount to a daily requirement per soldier of 0.65kg and 238.43kg per year assuming 3100kCal/kg as calorific content of grain. In addition, van Dinter *et al.* (2013) based their calculations on 50% of the total grain required by inhabitants of military and civilian settlements being supplied by rural agrarian settlements. In this study however, calculations were made assuming different percentage supplied by local farmers: 10-100%.

An alternative method of estimating the grain required by soldiers in the Dutch *limes* zone is to use information known regarding the rationing system of the Roman army as a basis for calculations. The rationing system is known only from a few sources however (Roth 1999, 19). Polybius (*Hist.*, 6.39.13-14) claimed that an infantryman (allied or Roman) received 2/3 Attic *medimnos* per month of wheat or four *modii*. The equivalent daily ration, Roth (1999, 24) argued, is 850g per day per soldier (c.f. Labisch 1975, 32-3, Gentry 1976, 25, Le Roux 1994, 408 & Junkelmann 1997, 91 who claim daily ration was 1kg; Engels 1978, 123 & Goldsworthy 1996, 291 who estimate daily ration at 1.4kg; and Kissel 1995, 35 who estimates 700g per day). It could be inferred also that the lack of difference in rations for legionaries and allied soldiers in the Republican period may also be true of auxiliaries and legionaries in the Imperial period. Polybius (*Hist.*, 6.39.13-14) also noted that infantrymen and cavalrymen received a different ration. A Roman cavalryman received two *medimnoi* of wheat and an allied cavalryman received $1\frac{1}{3}$ *medimnoi*. Using the above assumptions, a cavalryman would receive between eight and twelve *modii*, or between c. 54 and 81 kg, per month. This ration may not have been meant for one person however but would have been shared among the cortège of the cavalryman (see e.g. Donaghy 2012, 311; Erdkamp 2011, 102).

Neither method produces any certainty. Estimates based on the assumed calories required by soldiers rely on the accuracy of a number of assumptions: the calories required by soldiers, the proportion of the diet of soldiers fulfilled by grain and the calorific content of grain in the past. In addition, these calculations depend on a soldier's ration reflecting what was required rather than what was given. In comparisons with estimates based on what is known about rationing in the Roman army, van Dinter *et al.*'s (2013) estimate of 650g per day seems low. In contrast, Polybius' observations reveal precisely what was provided to the soldiers as part of their ration. However, the modern equivalent of these rations cannot be calculated with such precision. Translating the Greek measurements of volume (*medimnoi*) provided by Polybius to Roman measurements of volume (*modii*) and converting these to modern measurements of weight involve uncertainties at each step. In addition, the observations of the Republican army by Polybius may not reflect the situation in the Imperial army e.g. rations may have fluctuated and there is no information regarding auxiliaries in the army. Roth (1999, 19) claimed that the situation would not have changed, however. In addition, whether Polybius implied that a cavalryman's wheat ration was designated for multiple people is not certain. The estimates of daily rations for soldiers and cavalrymen provided in table 7.10, are therefore conjectural and calculated based on the mean values of multiple assumptions that fall between 650g per day (van Dinter *et al.* 2014) and 1.4kg (Engels 1978, 123 & Goldsworthy 1996, 291). Although estimates are given for the different rations for different military personnel, the calculations used in table 7.10 assume only the requirement per soldier. The extra quantity required by the cortege of the cavalry units has not been included because of difficulties in identifying where and for how long cavalry units were based in the fortifications of the Dutch *limes* zone. It reduces the number of possible combinations of assumptions used in this study also. It is recognised however that based on the data provided in table 7.10, a probable underestimation of the grain required during some periods and in some military settlements.

CATEGORY	UNIT	DAILY RATION/REQUIREMENT (KG)	NOTES
Infantryman (legion)	per soldier	1	Wheat, mean various estimates
Infantryman (auxiliary)	per soldier	1	Wheat, assuming no difference between Roman and auxiliaries
Cavalryman (legion)	per soldier	3	Wheat, probably for multiple people, assuming differences between Roman and auxiliary same as Republican differences between Roman and allied.
Cavalryman (auxiliary)	per soldier	2	Wheat, probably for multiple people, assuming differences between Roman and auxiliary same as Republican differences between Roman and allied.
Civilian (vicus)	per family unit	2.5	Wheat, based on requirements for one household as simulated in ROMFARMS
Horse (military)	per horse	4.6	Barley, mean various estimates

Table 7.10. Daily grain requirements/rations per consumer type in military and urban settlements.

Calculating the requirements of the civilian population living in the *vici* and the two *civitas* capitals is more complicated. It is probable that the population was heterogeneous comprising multiple families of children, adults and the elderly. For the calculations used in this analysis therefore the total population of the civilian settlements has been recalculated to reflect the number of households in each civilian settlement, using the results from simulating household population dynamics discussed in chapter 4. These results showed that a single household comprising approximately 5 individuals required c. 918kg of grain per year when 67.5% of the total diet of the inhabitants was grain-derived. With between 250 and 600 individuals estimated

per *vicus* following different assumptions, between 49 and 117 tons of grain could have been required per *vicus* per year, with more required for the larger settlements at Voorburg, Nijmegen. The daily grain requirement for a family of non-agrarian civilians residing in one of the *vici* in the study region is 2.5kg (see table 7.10).

7.4.1.3. Other uses for grain

It has been generally assumed that the grain consumed by soldiers in the Roman army was spelt wheat (*T. spelta*) or bread wheat (*T. aestivum*). In contrast, archaeobotanical assemblages from rural settlements in the Dutch *limes* zone indicate that six-row barley (*H. vulgare*) and emmer wheat (*T. dicoccon*) were the main cultivated cereals, with the cultivation of spelt wheat limited to the cover-sand areas north and south of the Rhine in the east of the Netherlands. Both spelt wheat, emmer wheat and barley have been found within assemblages from military sites in the Dutch *limes* zone, however. This would indicate that either the Roman military diet was mixed in these settlements with spelt, emmer and barley consumed, or that emmer wheat and barley were used for other purposes by the inhabitants. Despite barley being unpopular among ancient authors and the contention concerning human consumption of barley (see Polybius, *Hist.*, 6.38.3-4; Plutarch, *Ant.*, 39.7; Vegetius, *Mil.*, 1.13; Suetonius, *Aug.*, 24; Frontinus, *Strat.* 4.1.25,37 & Livy, *a.U.C.*, 27.13.9 for barley as punishment ration, see also Davies 1971), evidence from Northern Britain, where barley was a suitable crop for the local climate, pointed to consumption of the grain via both indirect evidence (cleaned and hulled barley) and direct evidence (bran fragments in human faecal remains) (Britton & Huntley 2011). Of course, these remains reveal nothing of the normalcy or regularity of barley consumption by Roman soldiers. The consumption of emmer wheat is less contentious.

The other hypothesis is that locally supplied cereals, particularly barley, were used not for human consumption but as fodder for horses used by the garrisons (Wilmott 2001, 103). In this scenario, the quantity of grain needed by the military settlements must be recalculated to reflect the needs of equids and not humans. In addition, it is possible that barley was used for the brewing of beer. Although there is no evidence for a regular ration of beer for Roman soldiers (Roth 1999, 40), 'Roman soldiers certainly drank beer' (ibid.; see also Davies 1971, 133; Junkelman 1997, 180). Beer was not a staple for either soldiers or civilians inhabiting *vici*. As such, demand for barley for beer production cannot be estimated from the calorific requirements of inhabitants nor what is known regarding standard provisioning of the Roman army. Accordingly, in contrast to the possible demands of grain for human consumption or the demands of grain for animal fodder, surplus production of barley for beer production is not considered in any calculations.

7.4.1.3.1. Estimating the equid population and fodder demand

The grain fodder required by military garrisons is determined by the number of equids in service and the requirement per horse. Unfortunately, only relatively uncertain estimates of the number of horses per military installation can be made. *Castella* manned by a *cohors quingenaria peditata* would have contained no cavalrymen, whereas those manned by a *cohors quingenaria equitata* would have contained roughly 120 cavalrymen and therefore at least 120 horses. Epigraphic evidence from Vechten indicates the presence of the *cohors I Flavia Hispanorum*, therefore 120 horses, from 70 CE until 125 CE (Kooistra *et al.* 2013, 13), and afterwards the *ala I Thracum Victrix*, therefore 500 cavalrymen at least (ibid.). Dixon & Southern (1992, 27-28) refer to two ancient sources on the number of cavalrymen per legion: Josephus (BJ 3.120) and Vegetius (Mil. 2.6). Josephus, writing in the 1st century CE, writes that a legion possessed 120 cavalrymen. Vegetius, writing in the late 4th century CE, writes that a legion possessed 726 horsemen. Dixon & Southern (1992, 27) rightly point out however that Josephus' observations may not have been

true for the whole empire at the time. Owing to a lack of sources regarding the organisation of cavalry support units within Roman legions and that Josephus wrote during a period contemporaneous with at least part of the period of this study, 120 cavalry per legion is tentatively assumed. Very uncertain estimates of the number of cavalry for the whole region would be therefore 240 attached to the possible two legions present in the early camp at Nijmegen Hunerberg, 120 present in Utrecht in the Early Roman Period B until the Middle Roman Period A, 120-500 at Vechten during the Early Roman Period B and 500 here in the Middle Roman period B, and 120 attached to the legion based in Nijmegen during the Middle Roman period A (see table 7.11). This estimate concerns the number of cavalrymen in the region rather than the number of equids in the region. In particular, the estimates do not include the many other equids, such as donkeys and mules, that can not be estimated with any certainty (c.f. Erdkamp 2011, 102) and therefore, regrettably, not included in these calculations.

Numerous estimates have been provided for the daily ration of barley given to cavalrymen in the Roman army. A Republican source claims the monthly ration for a Roman cavalryman was seven Attic *medimnoi* and an allied cavalryman received five *medimnoi* (Polybius Hist., 6.39.12.). This would indicate 42 or 30 *modii* of barley per month per cavalryman, or c. 147 or 206kg (Donaghy 2012, 311). One *medimnos* equalled six *modii* (see Nepos, *Att.* 2, Cicero, *in Verr.* 3.42, 110; 49, 116; also Rickman 1980, 9). One *modius* contained c. 5kg (after Pliny, *NH* 18.11.62 who claims one *modius* of barley equalled 15 Roman *lbs* with one Roman *lb* the equivalent of 0.72 modern lbs see Rickman 1980, 9). Some have argued that this is not the total amount given to one horse per month but to the soldier, with one soldier feeding multiple animals with this amount. Accordingly, Walker (1973, 340) and Hyland (1990, 91) suggested 1.5kg per animal per day. Brereton (1976, 20) and Vossen & Groot (2009, 96) cited a higher quantity of 9 and 7kg respectively. These estimates may be erroneous by not differentiating between the rations given to cavalrymen meant for multiple animals and the quantity supplied to each horse. Van Dinter *et al.* (2014, 31) also cite a high daily ration (6.3kg) but acknowledge this is per cavalryman and not per horse. The rations assumed for this discussion are provided in table 7.10. As with estimates of the grain requirement for human consumption in military and civilian settlements, different proportions between 10 and 100% of the total amount required have been calculated, rather than, as van Dinter *et al.* (2014) assumed, that 50% was supplied by local settlements.

SUB-REGION	IJZL	ROMVA	ROMVB	ROMMA	ROMMB
1	0	0	0	0	0
2	0	0	0	0	0
3	0	0	0	0	0
4	0	0	0	0	0
5	0	0	0	0	0
6	0	0	240	240-620	500
7	0	0	0	0	0
8	0	0	0	0	0
9	0	0	0	0	0
10	0	0	0	0	0
11	0	0	0	0	0
12	0	0	0	0	0
13	0	0	0	0	0
14	0	0	0	0	0
15	0	0	0	0	0
16	0	0	0	0	0
17	240	0	0	120	0
18	0	0	0	0	0
19	0	0	0	0	0
20	0	0	0	0	0
21	0	0	0	0	0
22	0	0	0	0	0
23	0	0	0	0	0
24	0	0	0	0	0
25	0	0	0	0	0
26	0	0	0	0	0
27	0	0	0	0	0
28	0	0	0	0	0
29	0	0	0	0	0
30	0	0	0	0	0
31	0	0	0	0	0
32	0	0	0	0	0

Table 7.11. Estimated total number of cavalrymen per sub-region.

7.5. Supply and demand on a micro- and macro-regional scale: deficits and surplus

Comparisons between the demand in each sub-region and in the Lower Rhine delta in total with the potential local and regional supply of grain and animal products provide estimates of the possible surpluses and deficits of food when military settlements and *vici* are supplied by local rural settlements. Demand from consumer-only settlements such as *castella* and *vici*, and supply by local rural agrarian settlements differs depending on scenario. In scenarios where demand is low, the number of consumer-only settlements is low, or the proportion of the diet derived from locally-produced food is small, or the estimated population of each consumer-only settlement is low (or a combination of any of these factors). Scenarios where demand is high are characterised by relatively high numbers of consumer-only settlements, or the proportion of the inhabitants' diet in these settlements is high, or the estimated population of each *castellum* or *vicus* is high (or, again, a combination of these factors). Similarly, scenarios of local supply from agrarian settlements can be divided between high and low supply. The results of simulating agriculture and animal husbandry in randomly-generated landscapes show that scenarios of high supply include those with landscapes occupied by larger settlements with three or five households, and scenarios where settlements undertake extensification and extensive surplus animal husbandry. Scenarios with low local supply are those with small settlements with one household and those with settlements undertaking subsistence-based agriculture. Supply in sub-regions and in periods with a relatively high settlement density will also be higher as a result of more settlements occupying the landscape.

Comparing potential supply and demand over different geographic scales can also provide indications on the possible way that food was transferred from local agrarian settlements to consumer-only settlements. Two different scales have been envisaged: micro-regional and macro-regional. A micro-regional scale of supply is assumed to be where surplus grain and/or animal products produced by settlements in each sub-region is supplied to the military settlements or *vici* located in the region. A macro-regional scale of supply is assumed to be where the sum total of surplus grain and/or animal products produce in the Lower Rhine delta is supplied to all *castella*, *castra* and *vici* present in the whole study region. Although not considered here, a supra-regional scale exists also whereby consumer-only military and civilian settlements are supplied by agrarian settlements outside of the study region. When micro- or macro-regional demand outstrips supply on the same scale in a scenario, it is assumed that this mechanism is not feasible.

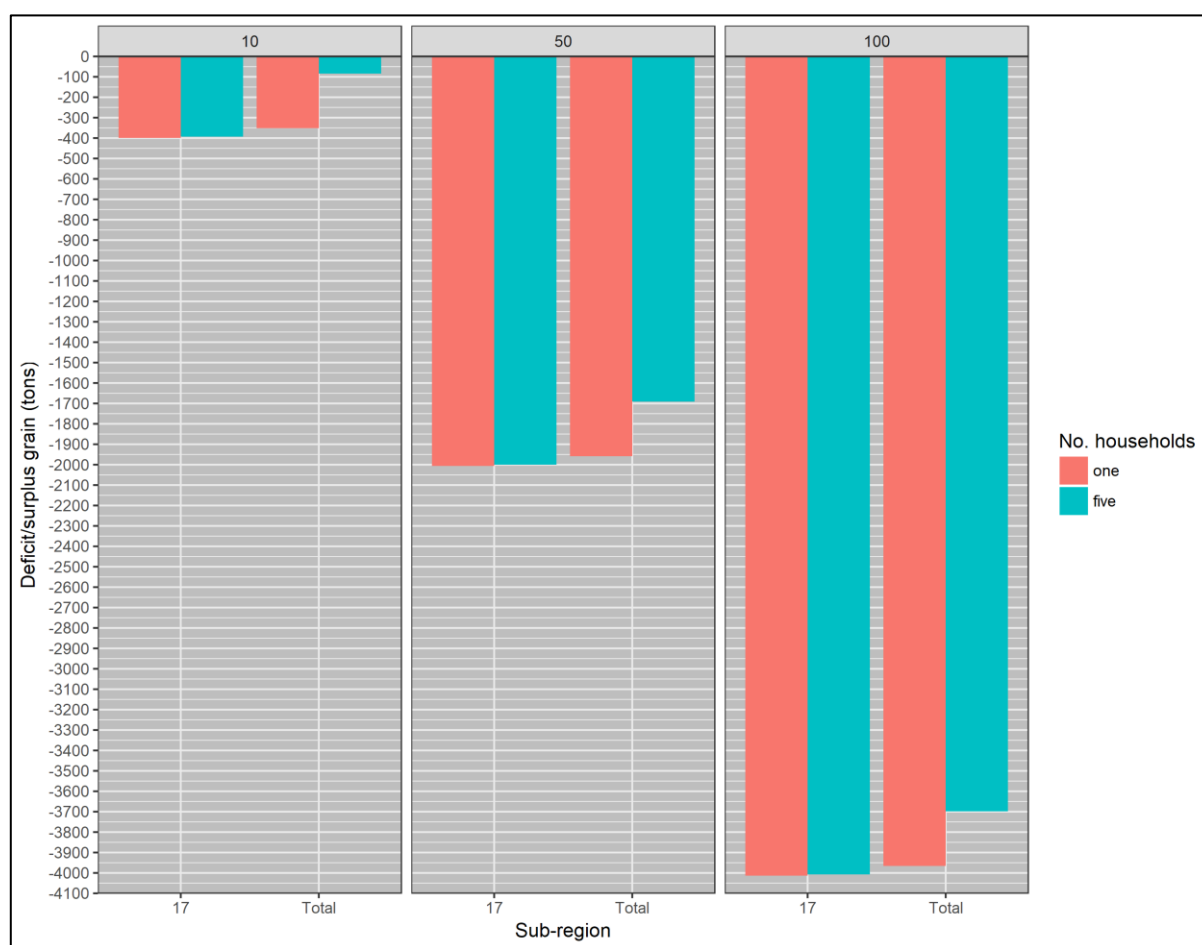


Figure 7.4. Micro- and macro-regional deficits (negative values) and surpluses (positive values) of grain required by soldiers in the Late Iron Age. NB for readability only the maximum and minimum production scenarios are included in the following figures i.e. landscapes with settlements with one household or five households. For this reason, also, the percentages of total grain required that is demanded from local rural settlements include only the minimum, median and maximum in the range of possible values (10, 50 and 100%).

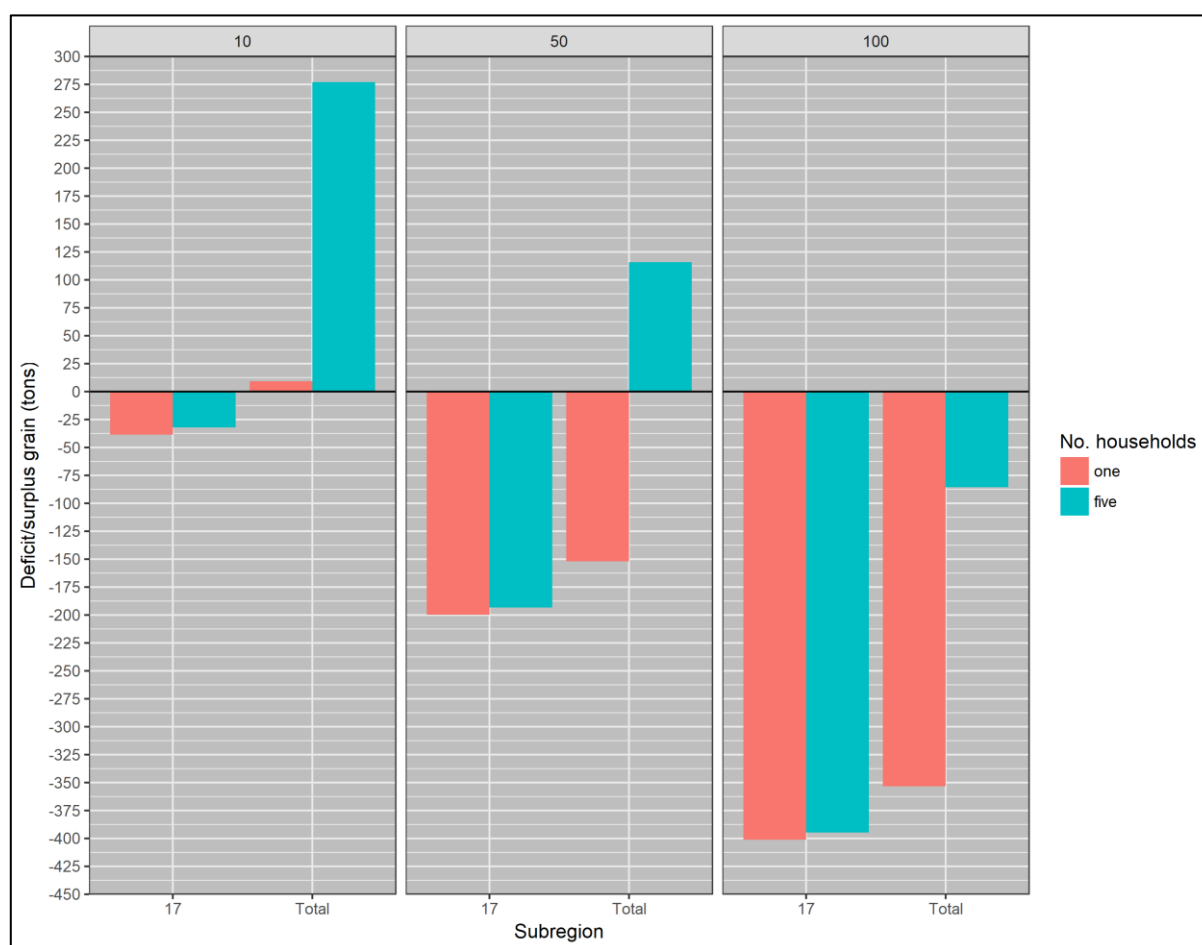


Figure 7.5. Micro- and macro-regional surpluses and deficits of the grain required by military equids in the Late Iron Age.

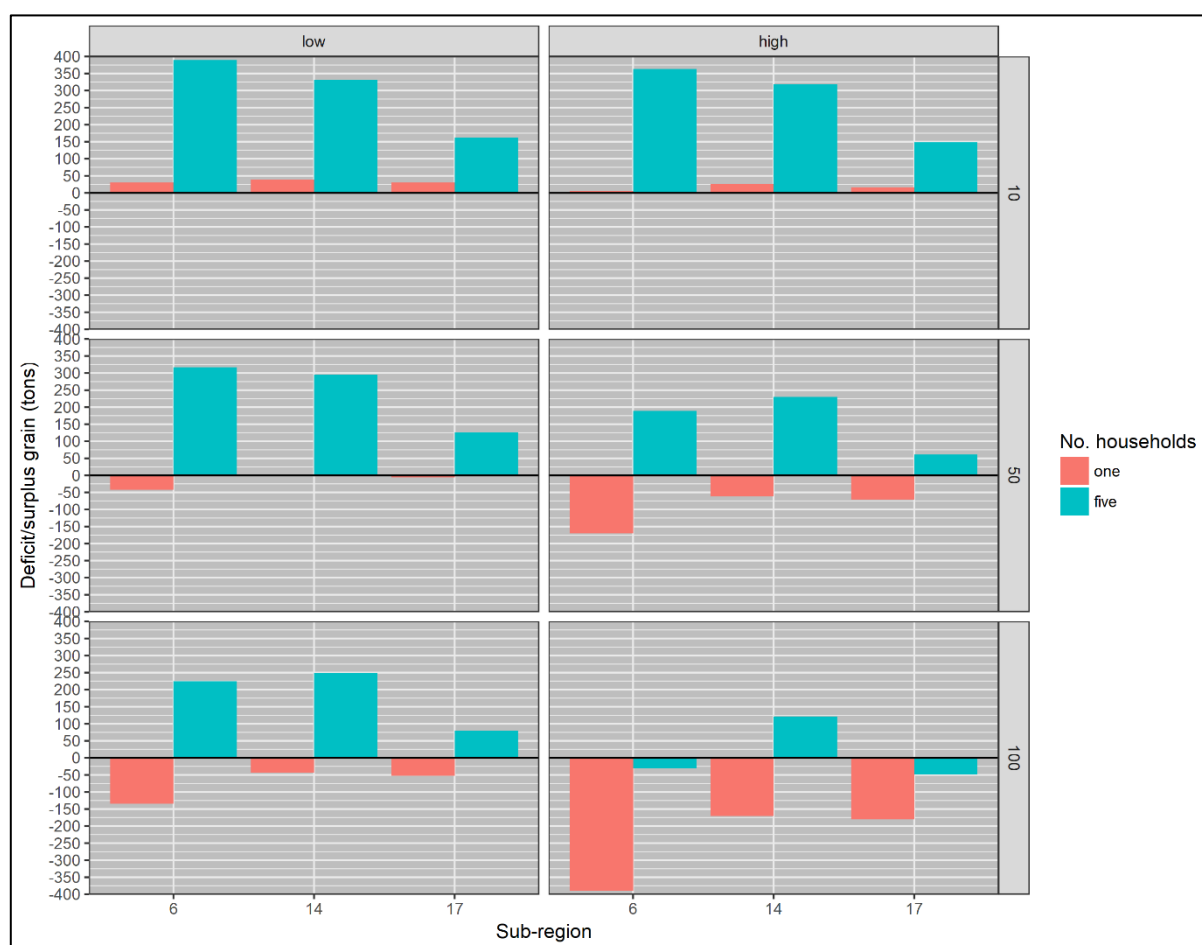


Figure 7.6. Micro-regional surpluses and deficits of the grain required by soldiers in the Early Roman Period A when settlements undertake arable extensification. NB the population estimates per military settlement used in figures in this chapter are the upper and lower estimates in the range (i.e. low and high; see tables 7.8, 7.9 & 7.11).

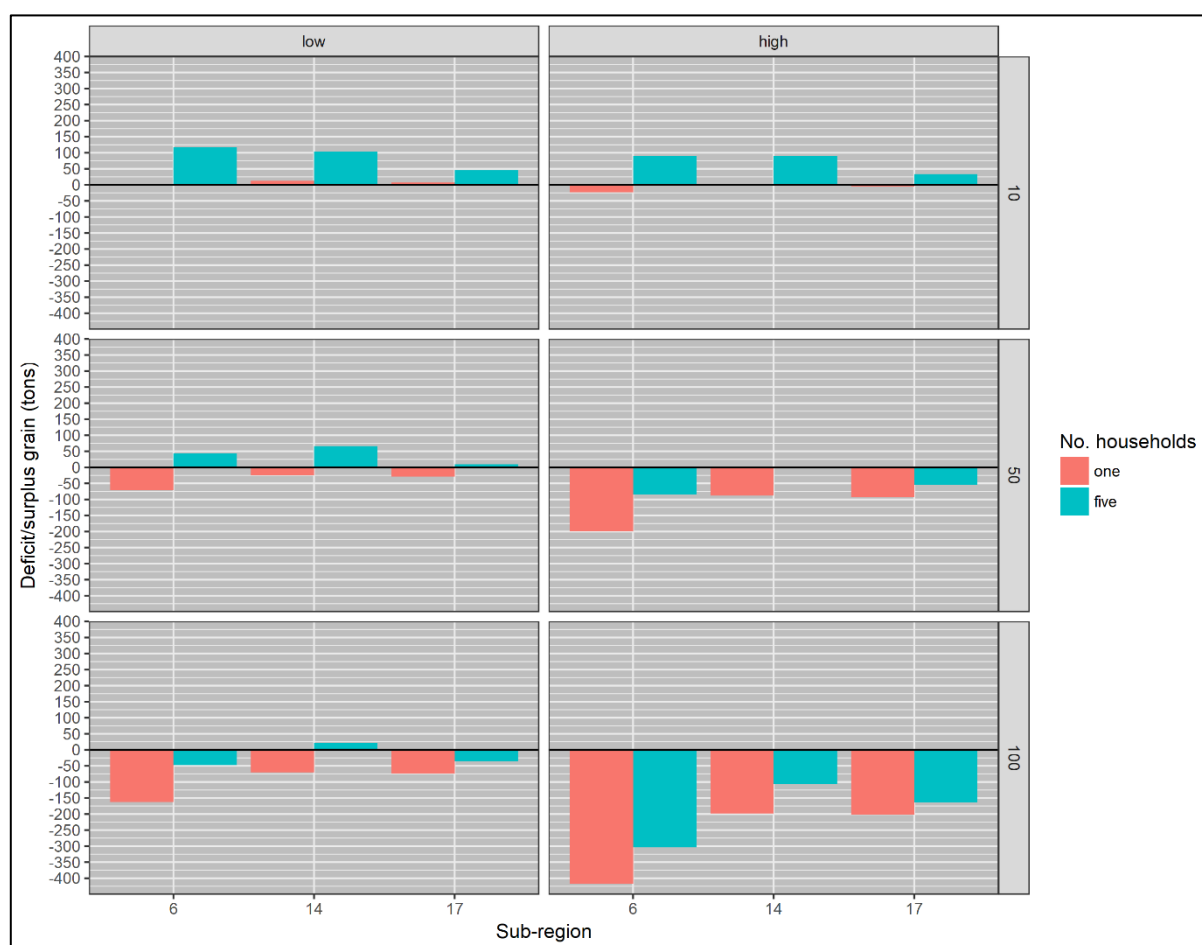


Figure 7.7. Micro-regional surpluses and deficits of the grain required by soldiers in the Early Roman Period A when settlements undertake arable intensification.

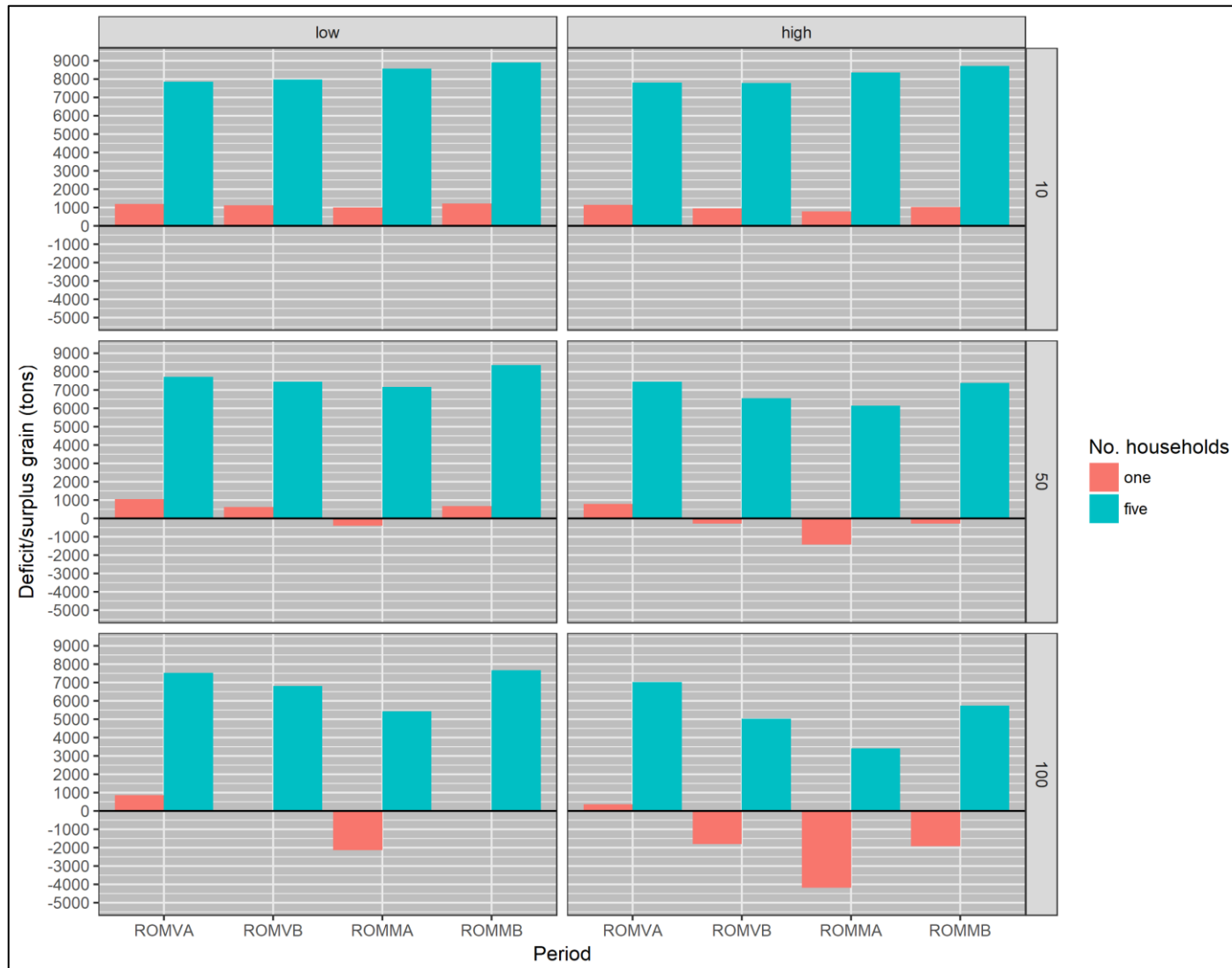


Figure 7.8. Macro-regional surpluses and deficits of the grain required by soldiers in all periods when settlements undertake arable extensification.

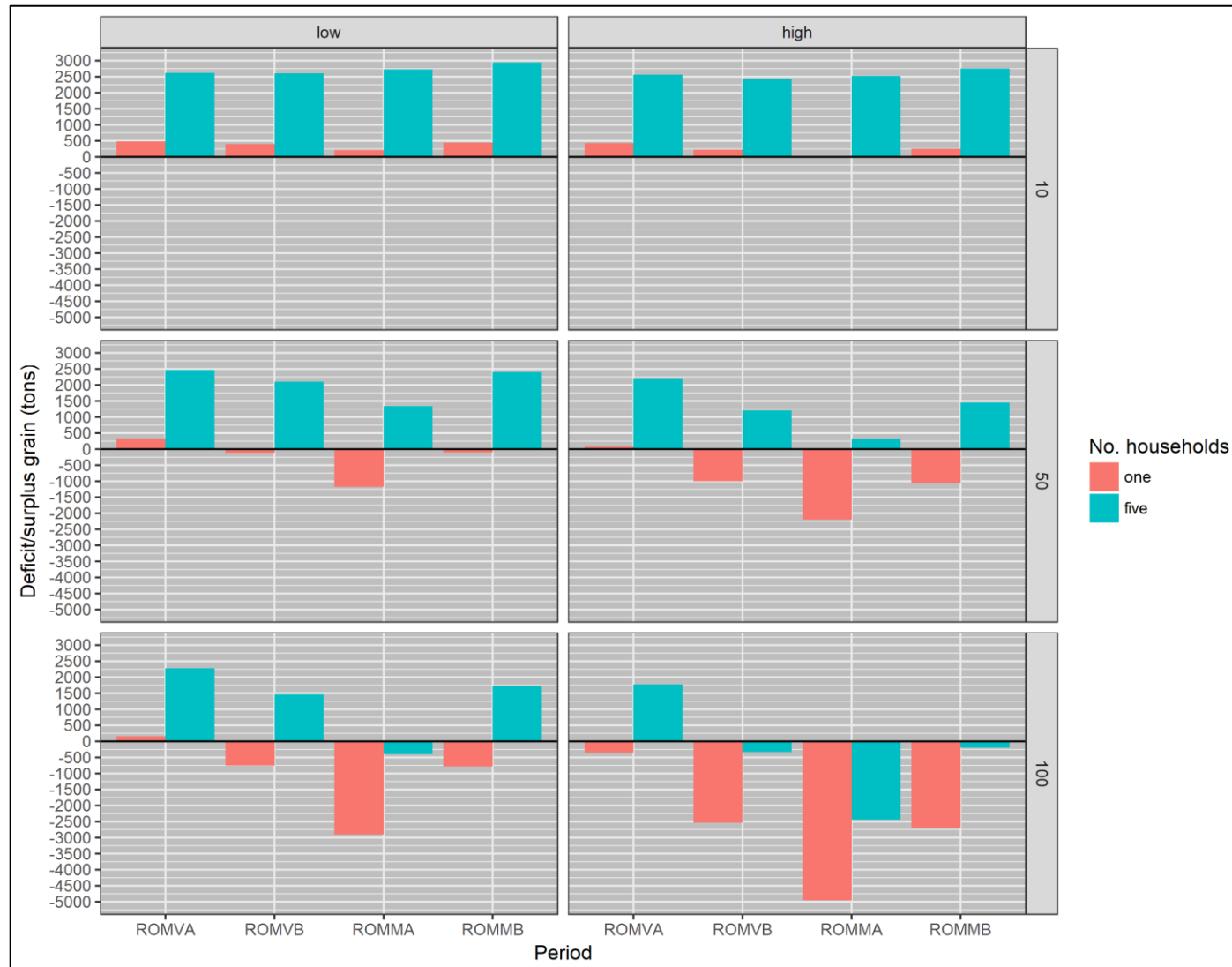


Figure 7.9. Macro-regional surpluses and deficits of the grain required by soldiers in the all settlements when settlements undertake arable intensification.

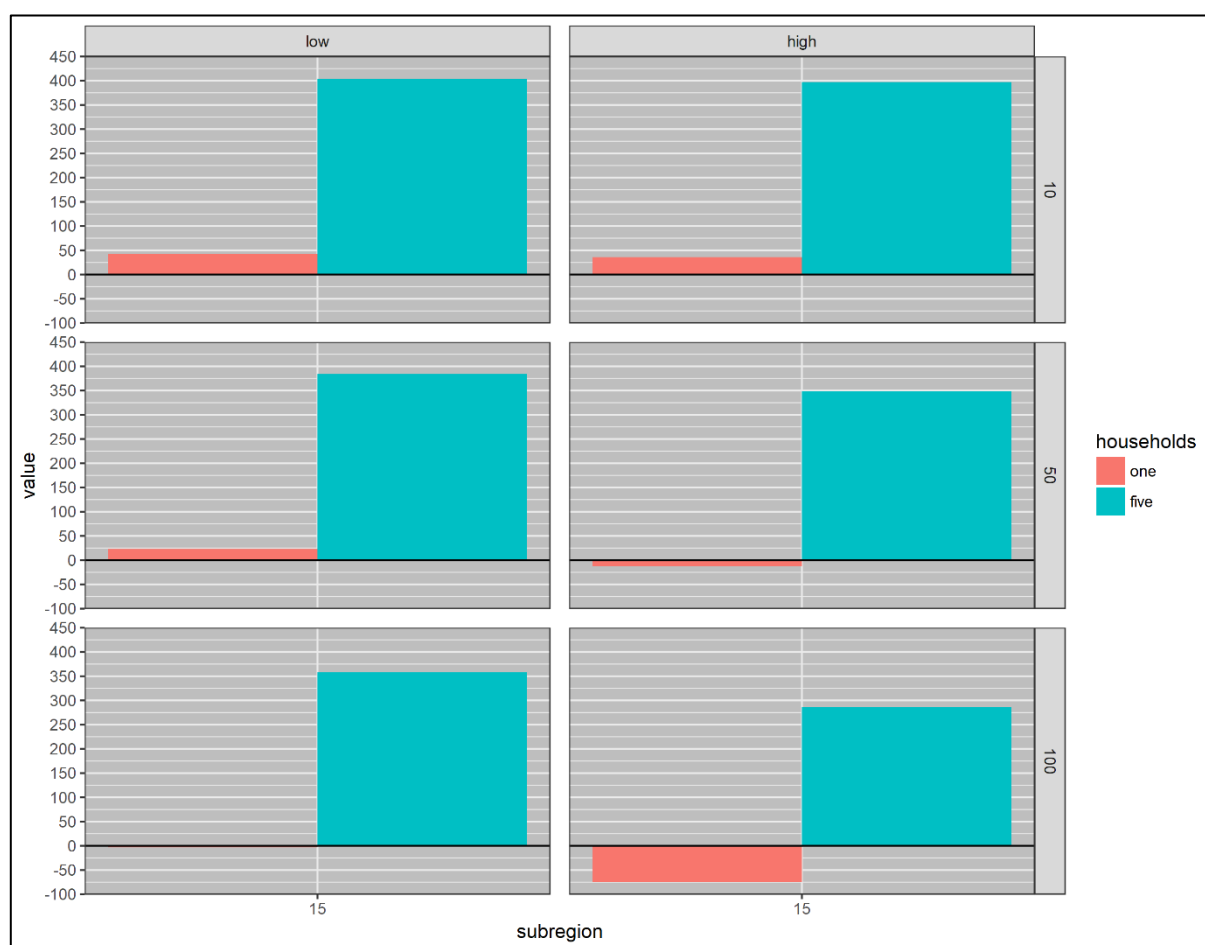


Figure 7.10. Micro-regional surpluses and deficits of the grain required by inhabitants of towns and vici in the Early Roman Period A when settlements undertake arable extensification.

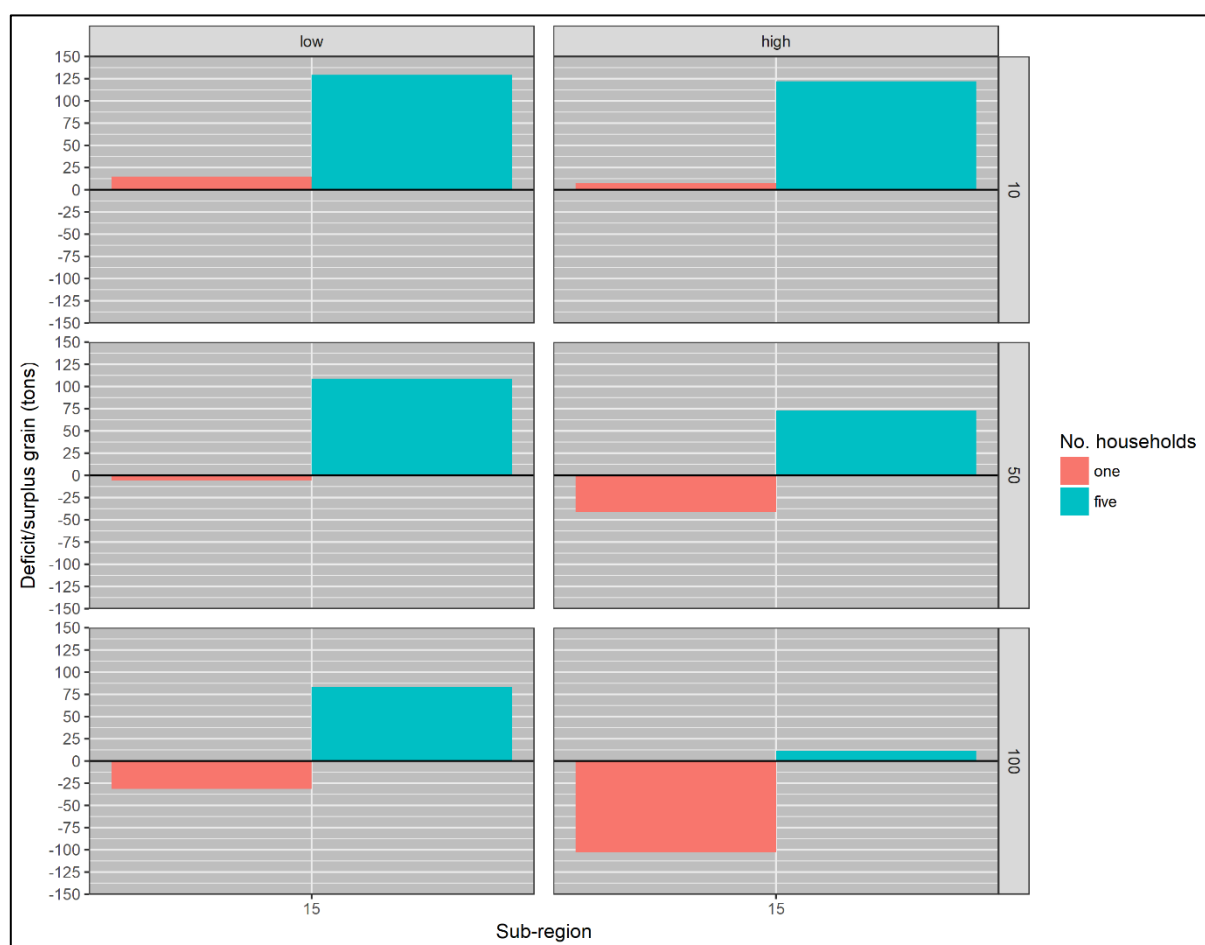


Figure 7.11. Micro-regional surpluses and deficits of the grain required by inhabitants of towns and vici in the Early Roman Period A when settlements undertake arable intensification.

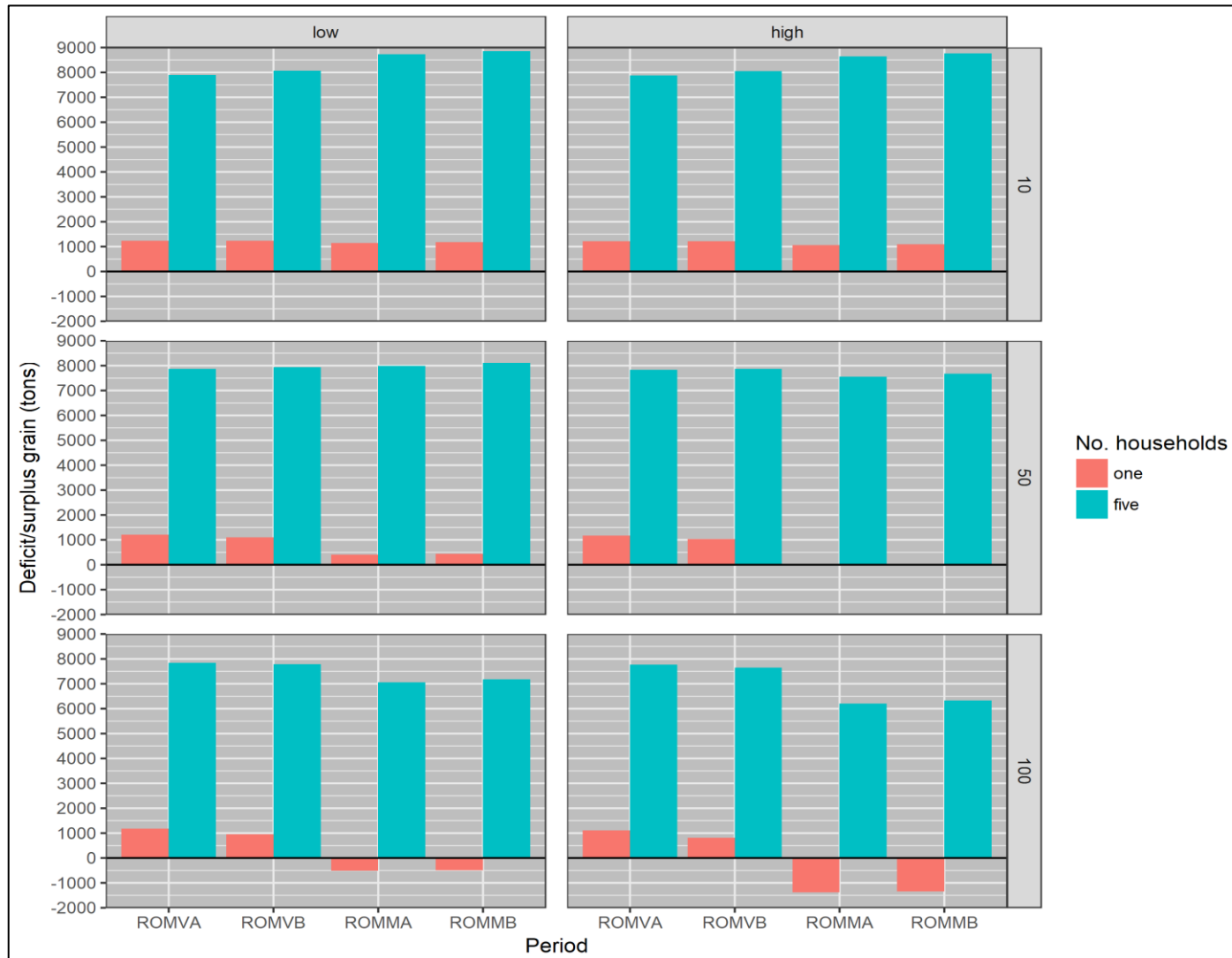


Figure 7.12. Macro-regional surpluses and deficits of the grain required by inhabitants of towns and vici in all periods when settlements undertake arable extensification.

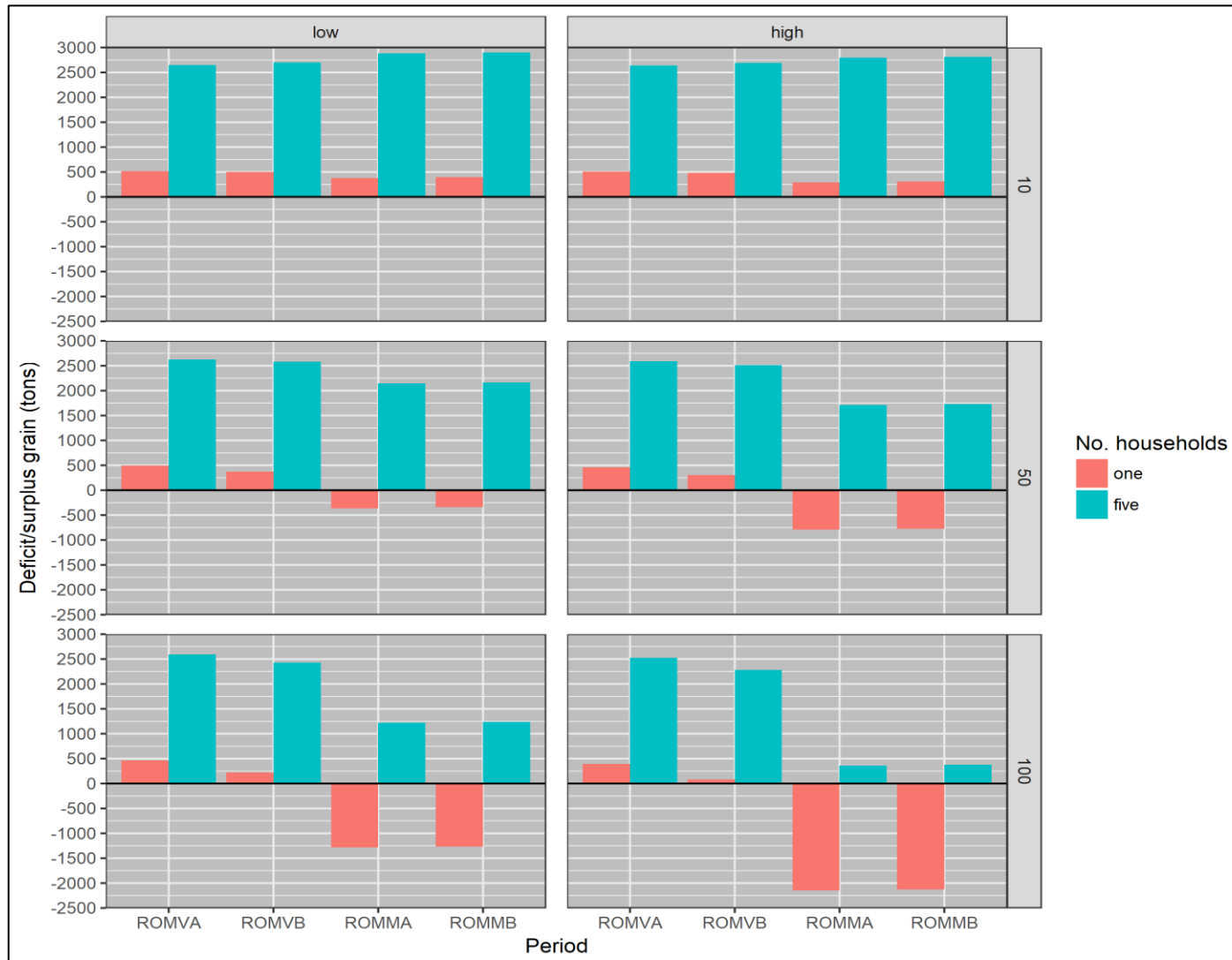


Figure 7.13. Macro-regional surpluses and deficits of the grain required by inhabitants of towns and vici in all periods when settlements undertake arable intensification.

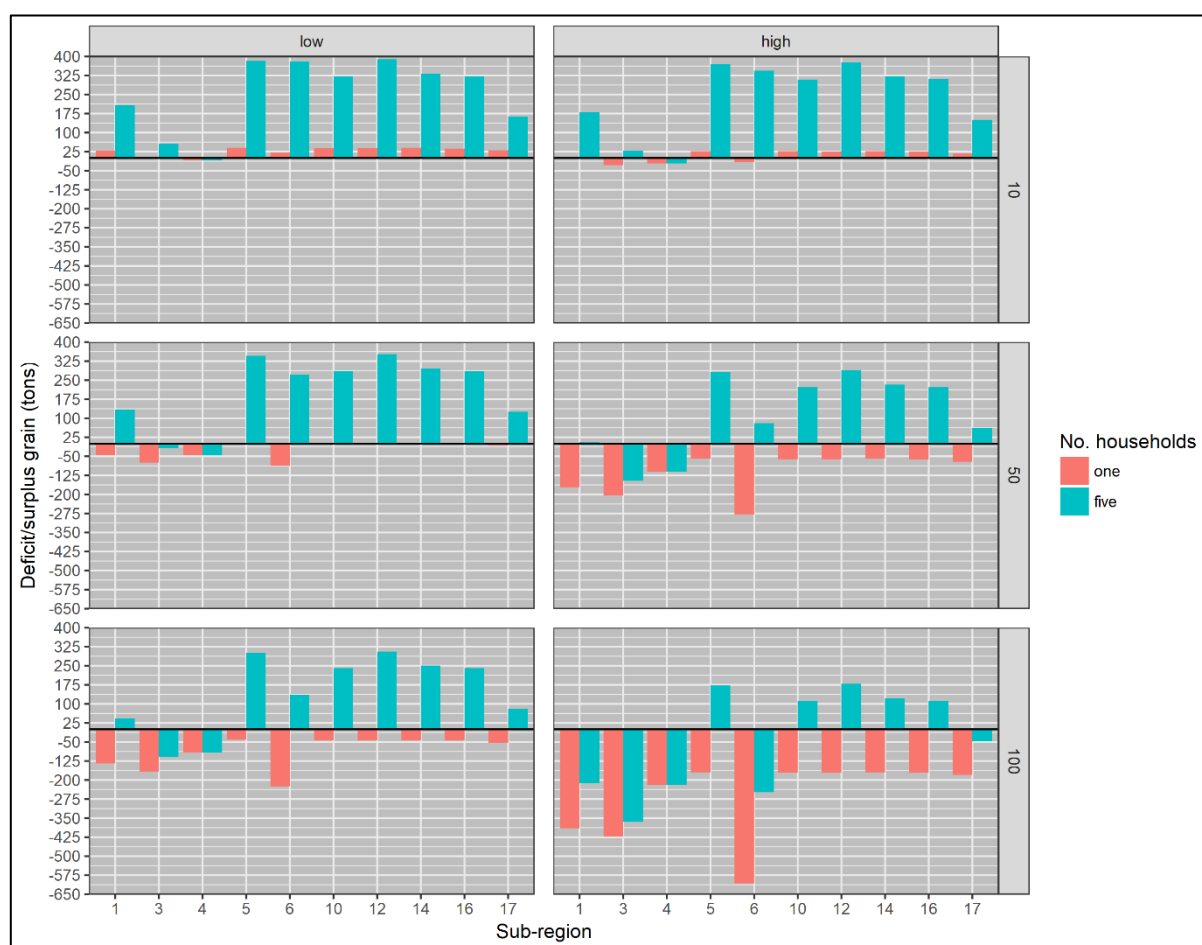


Figure 7.14. Micro-regional surpluses and deficits of the grain required by soldiers in the Early Roman Period B when settlements undertake arable extensification.

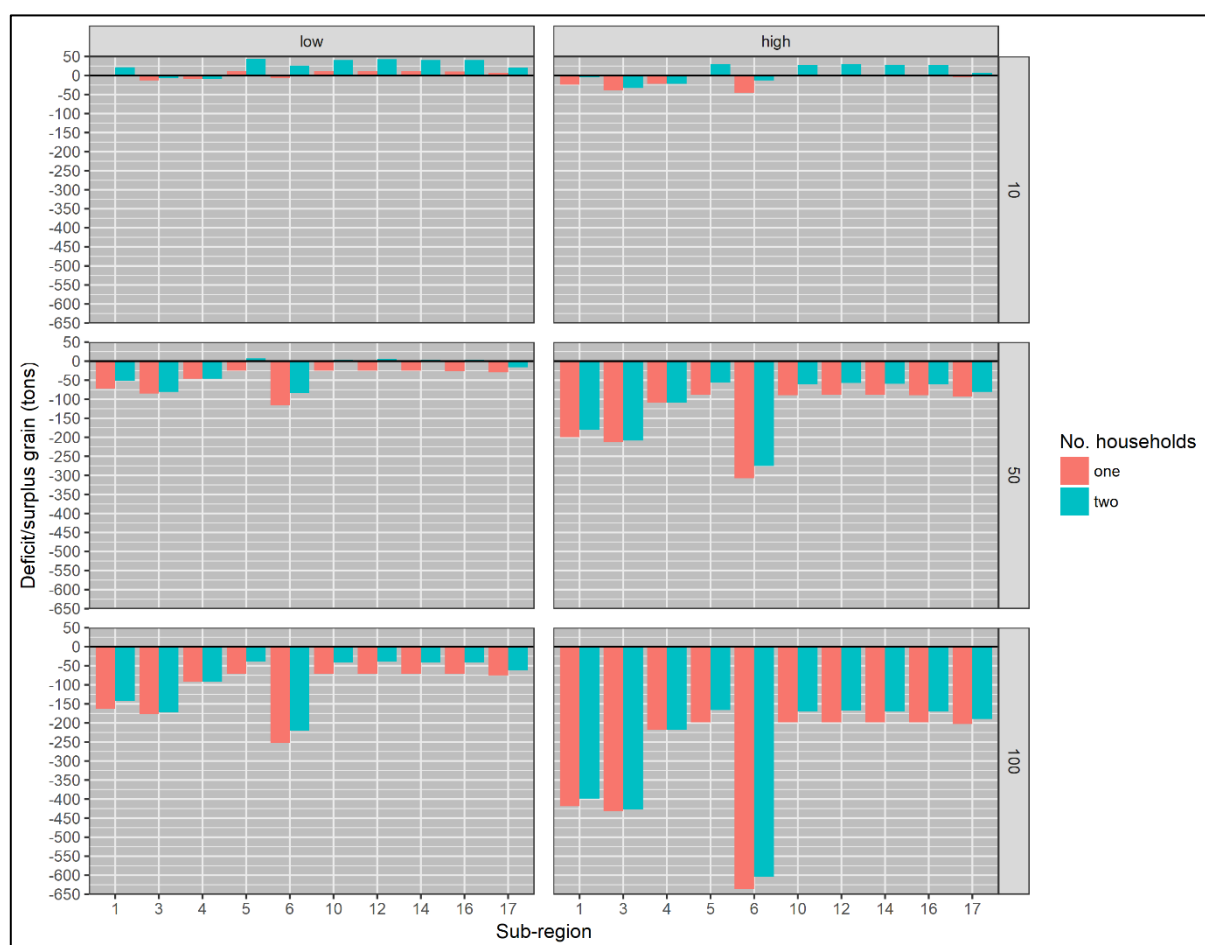


Figure 7.15. Micro-regional surpluses and deficits of the grain required by soldiers in the Early Roman Period B when settlements undertake arable intensification.

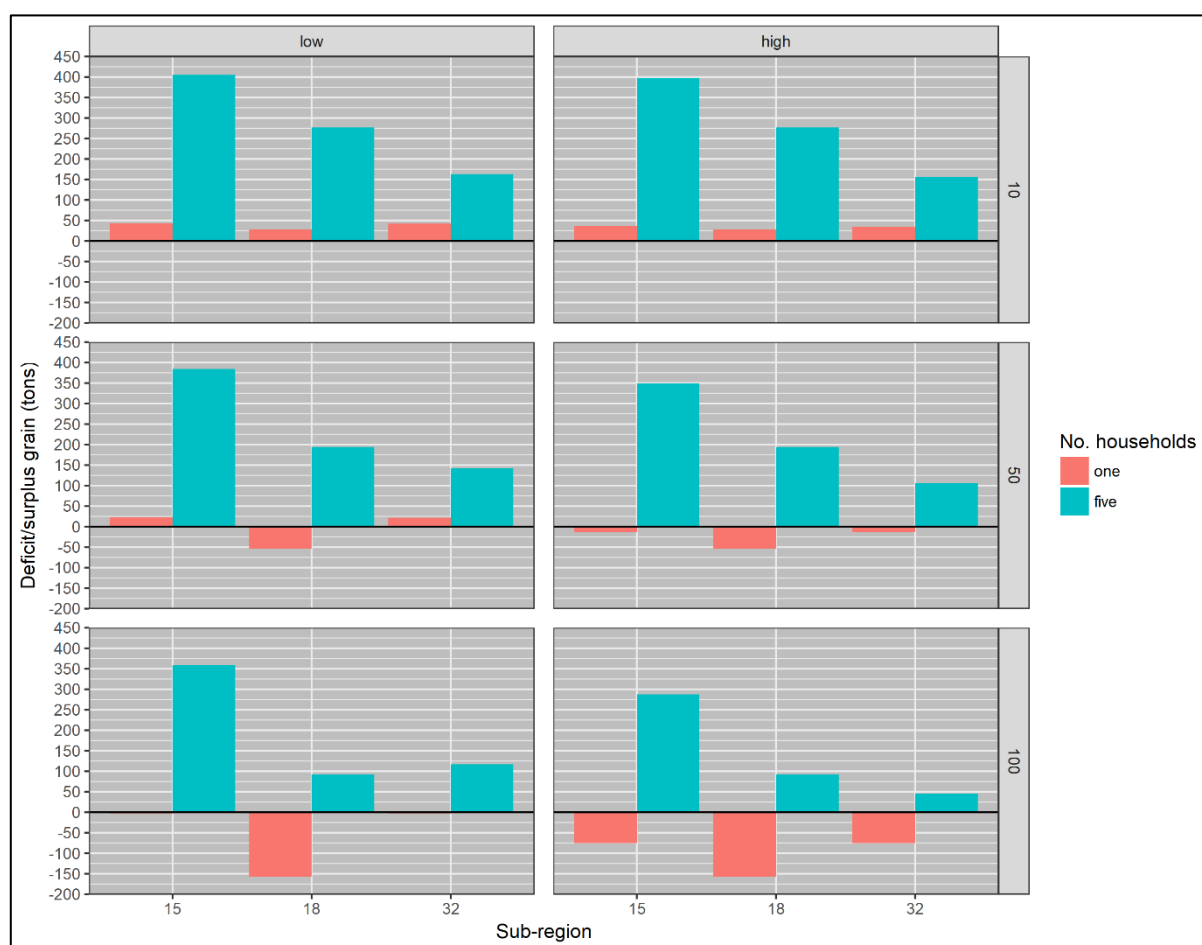


Figure 7.16. Micro-regional surpluses and deficits of the grain required by inhabitants of towns and vici in the Early Roman Period B when settlements undertake arable extensification.

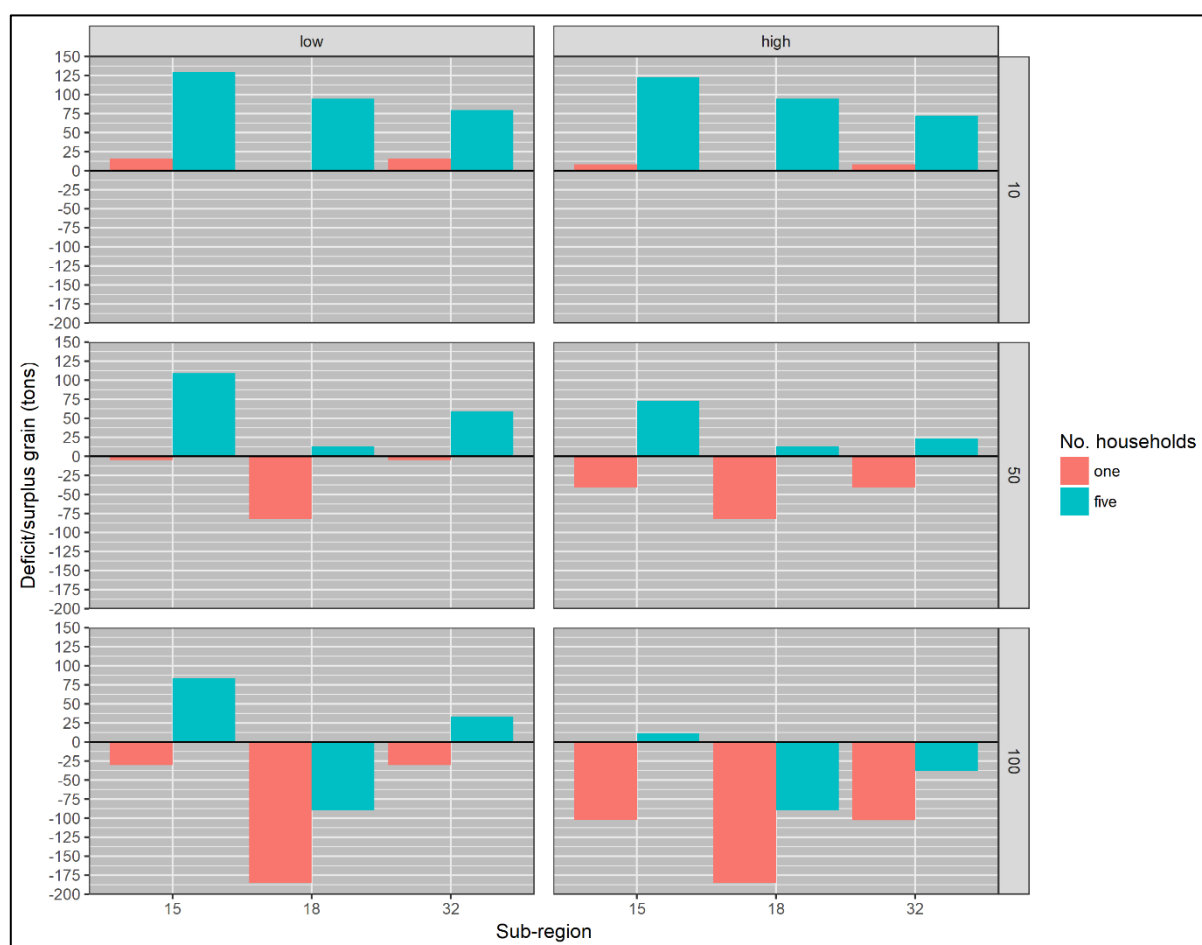


Figure 7.17. Micro-regional surpluses and deficits of the grain required by inhabitants of towns and vici in the Early Roman Period B when settlements undertake arable intensification.

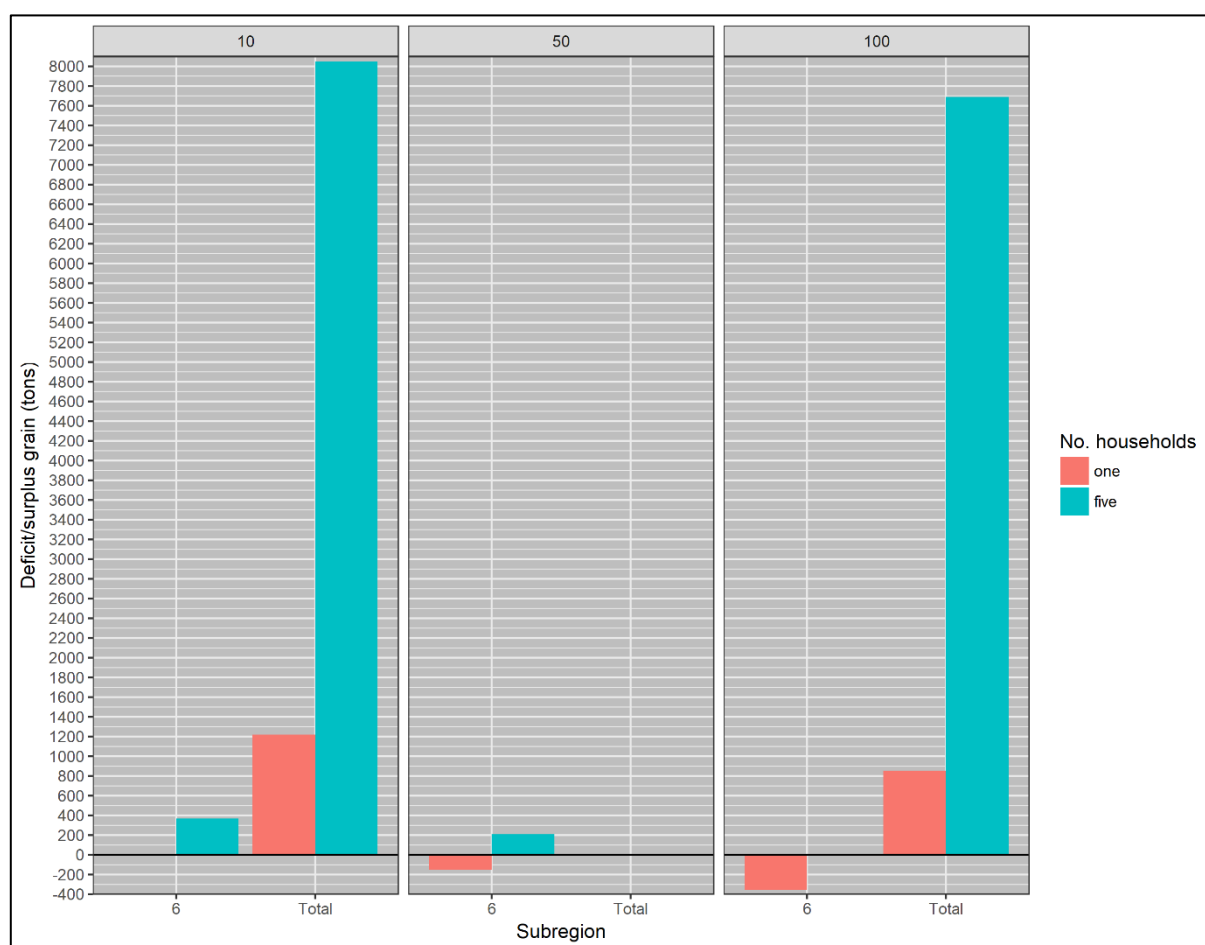


Figure 7.18. Micro- and macro-regional surpluses and deficits of the grain required by military equids in Early Roman Period B when settlements undertake arable extensification.

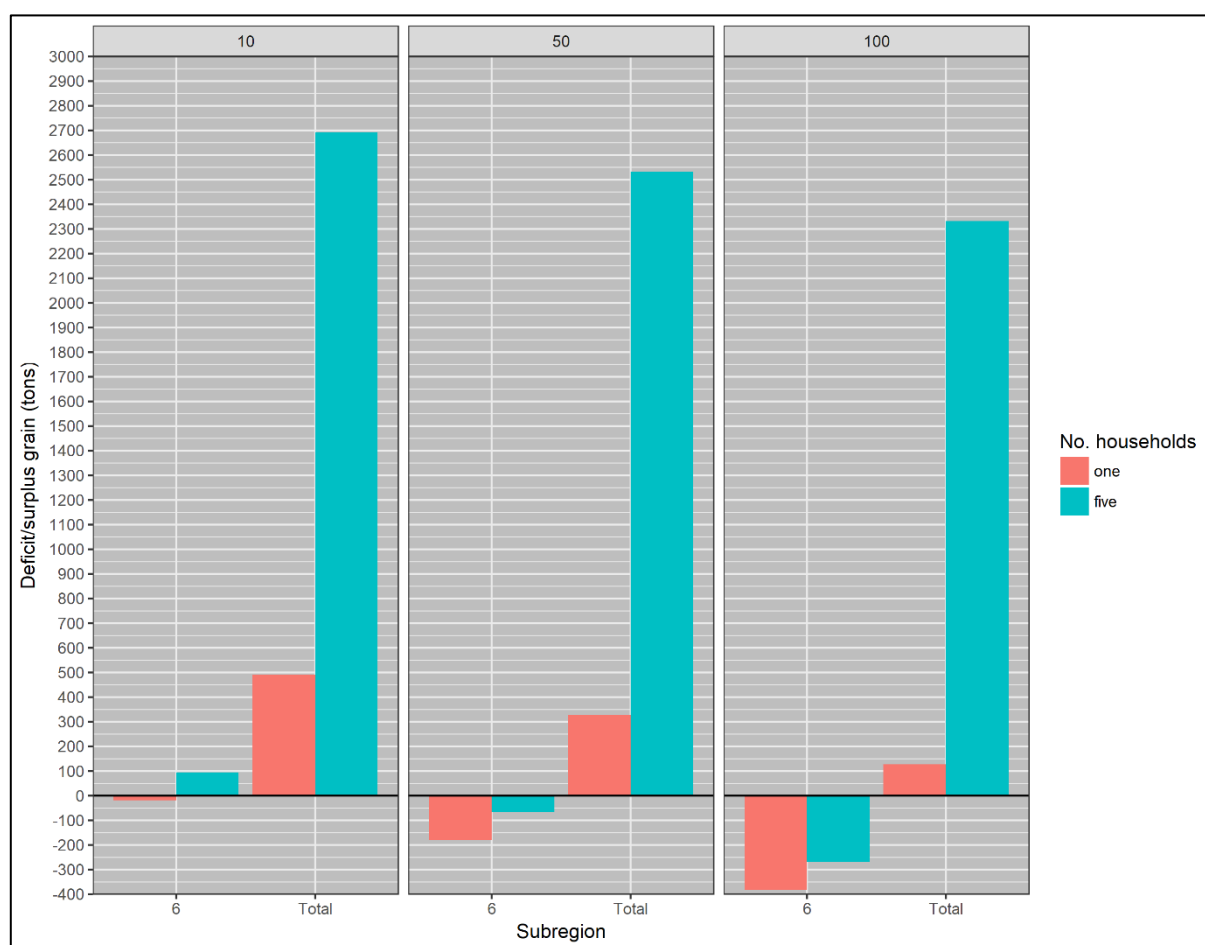


Figure 7.19. Micro- and macro-regional surpluses and deficits of the grain required by military equids in Early Roman Period B when settlements undertake arable intensification.

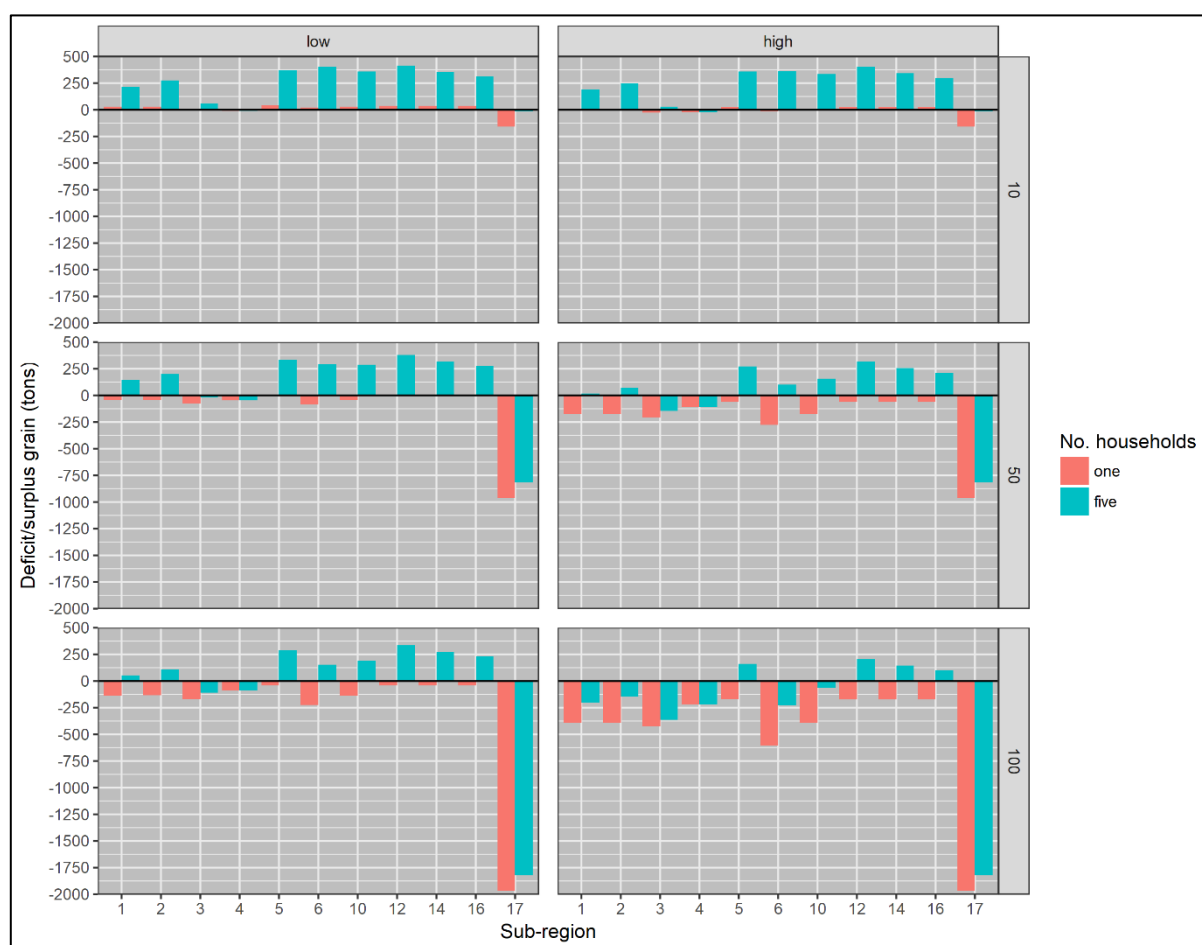


Figure 7.20. Micro-regional surpluses and deficits of the grain required by soldiers in the Middle Roman Period A when settlements undertake arable extensification.

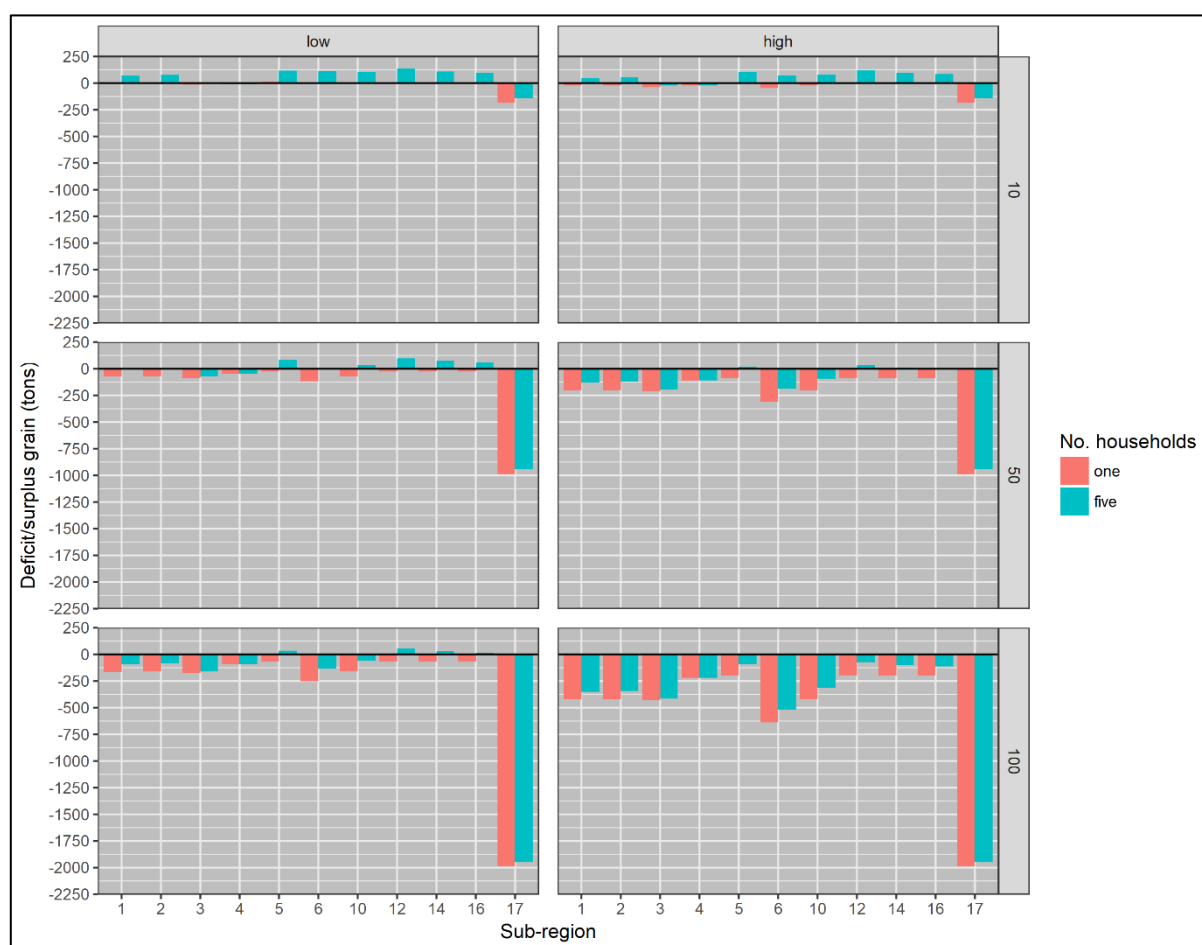
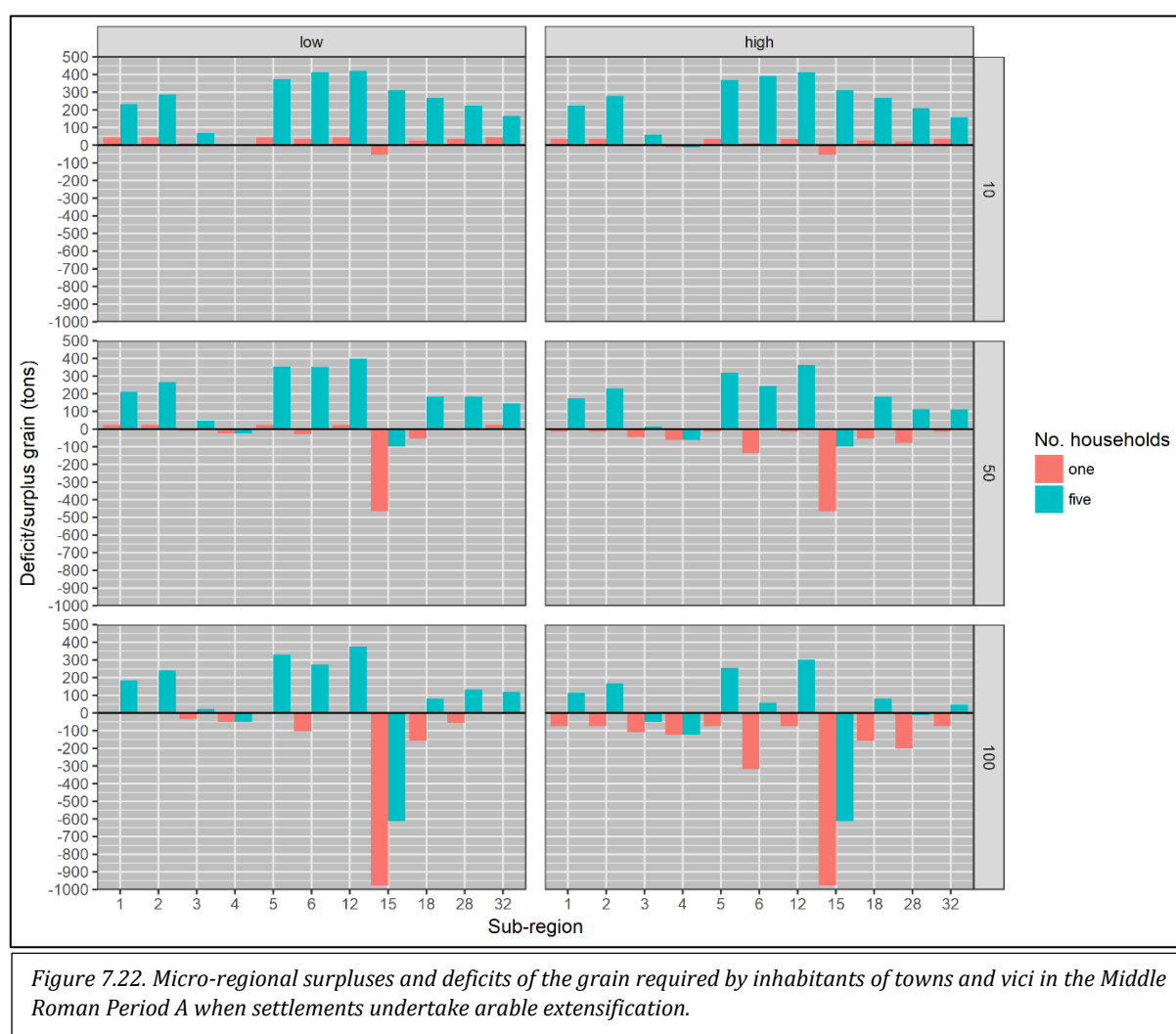
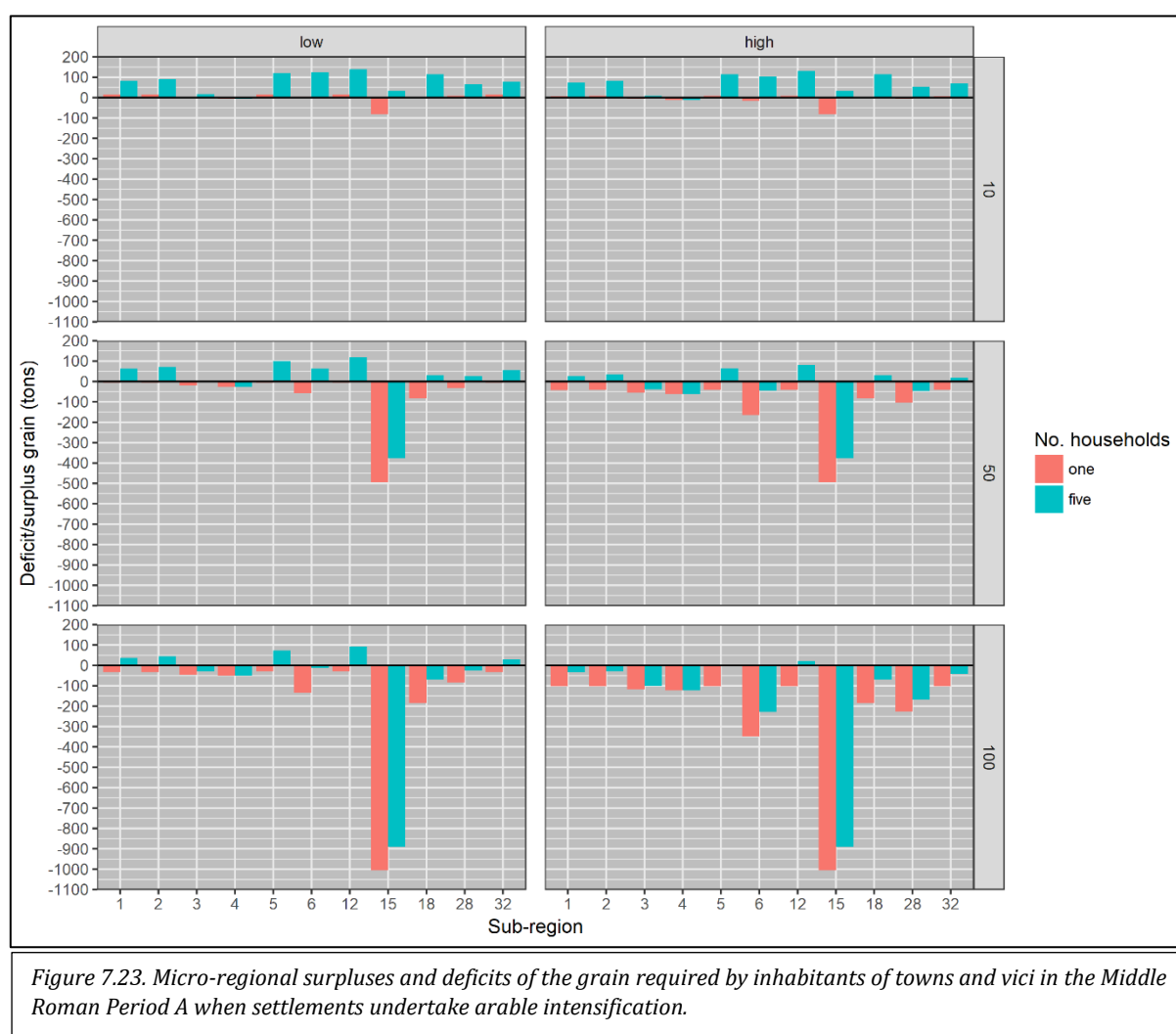


Figure 7.21. Micro-regional surpluses and deficits of the grain required by soldiers in the Middle Roman Period B when settlements undertake arable intensification.





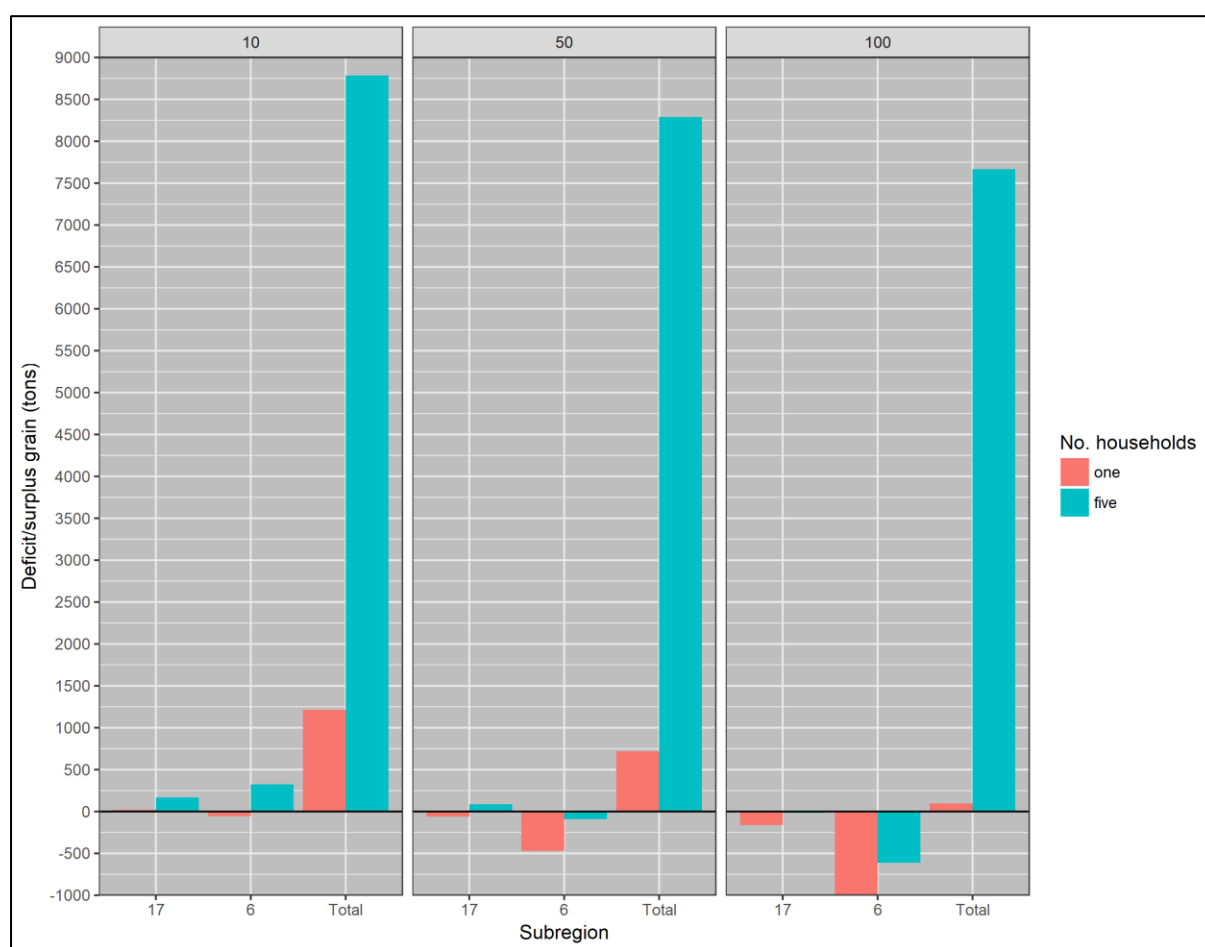


Figure 7.24. Micro- and macro-regional surpluses and deficits of the grain required by military equids in the Middle Roman Period A when settlements undertake arable extensification.

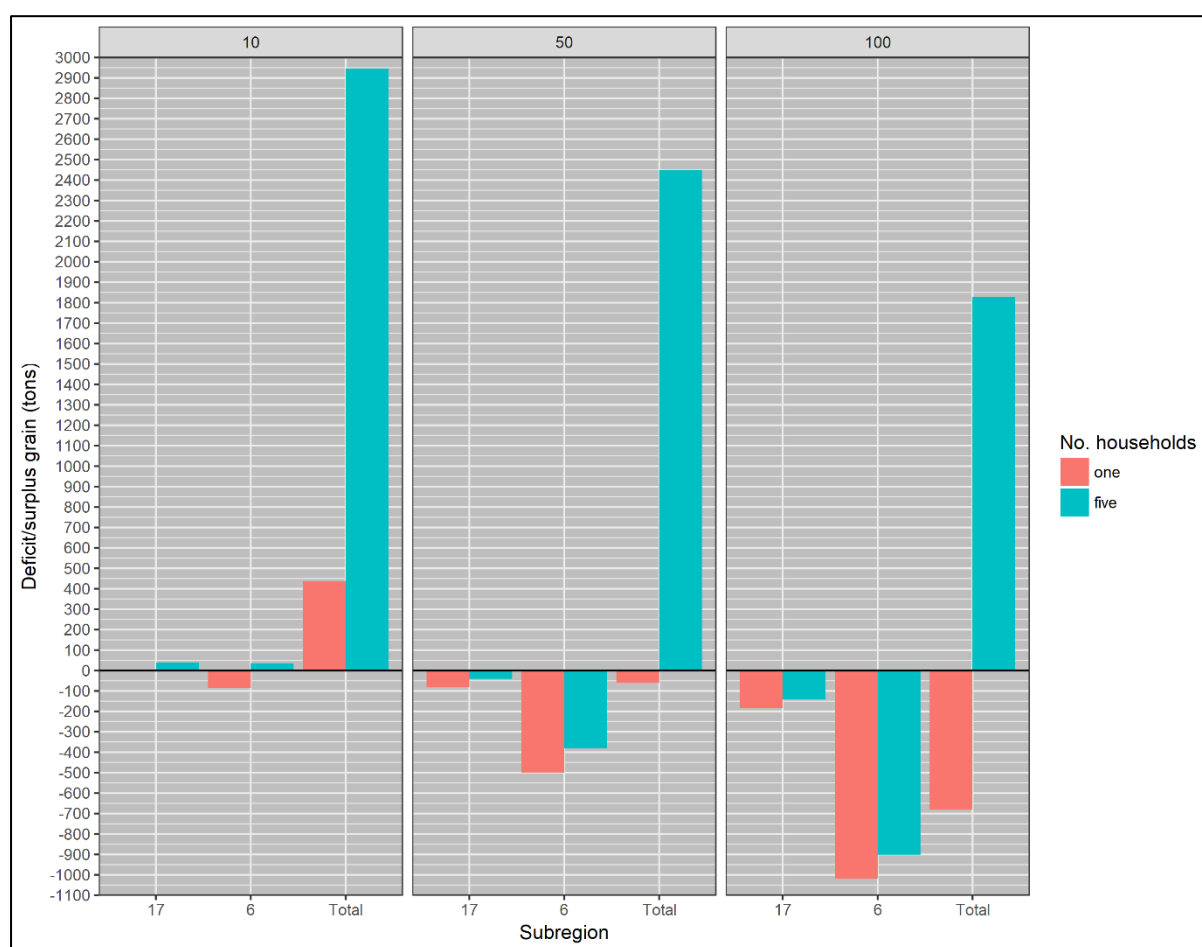


Figure 7.25 Micro- and macro-regional surpluses and deficits of the grain required by military equids in the Middle Roman Period A when settlements undertake arable intensification.

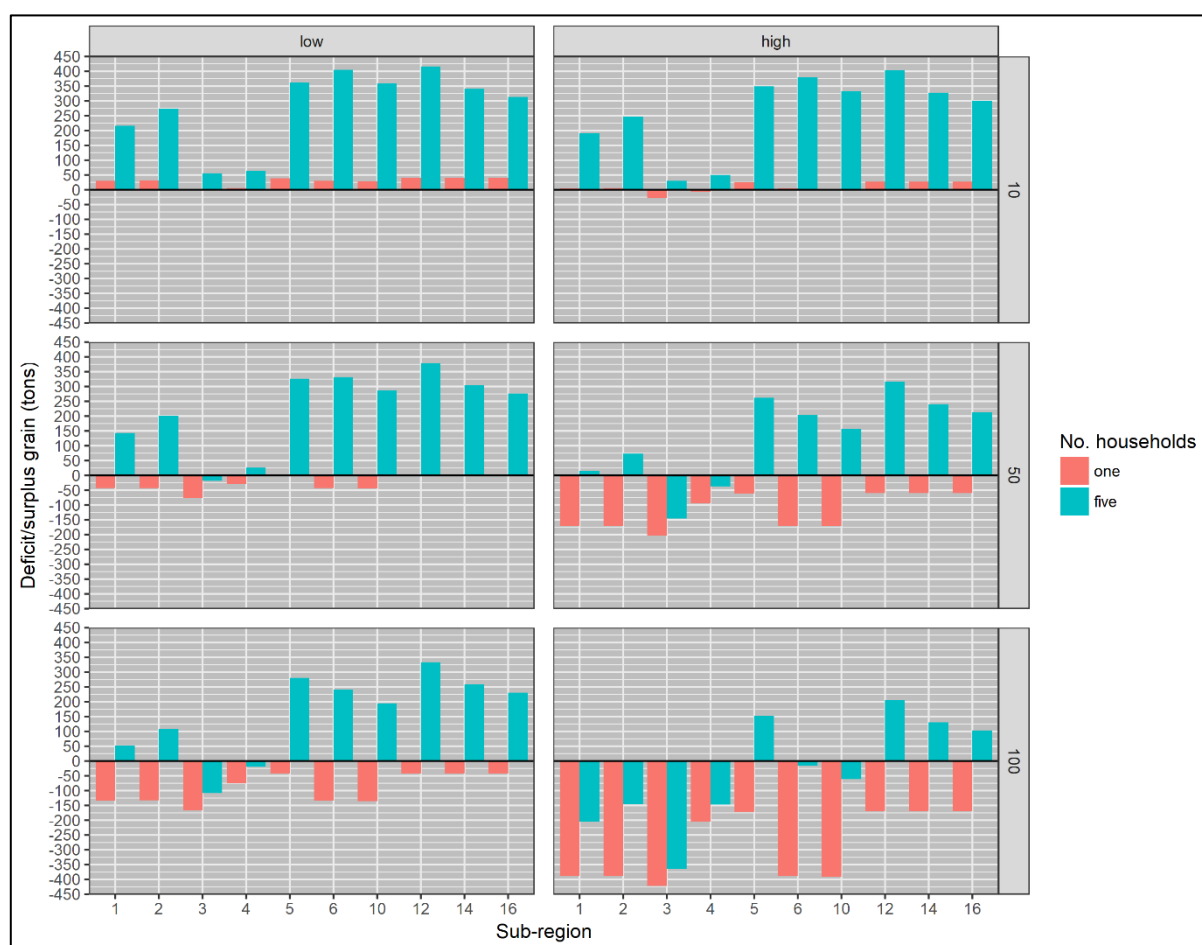


Figure 7.26. Micro-regional surpluses and deficits of the grain required by soldiers in the Middle Roman Period B when settlements undertake arable extensification.

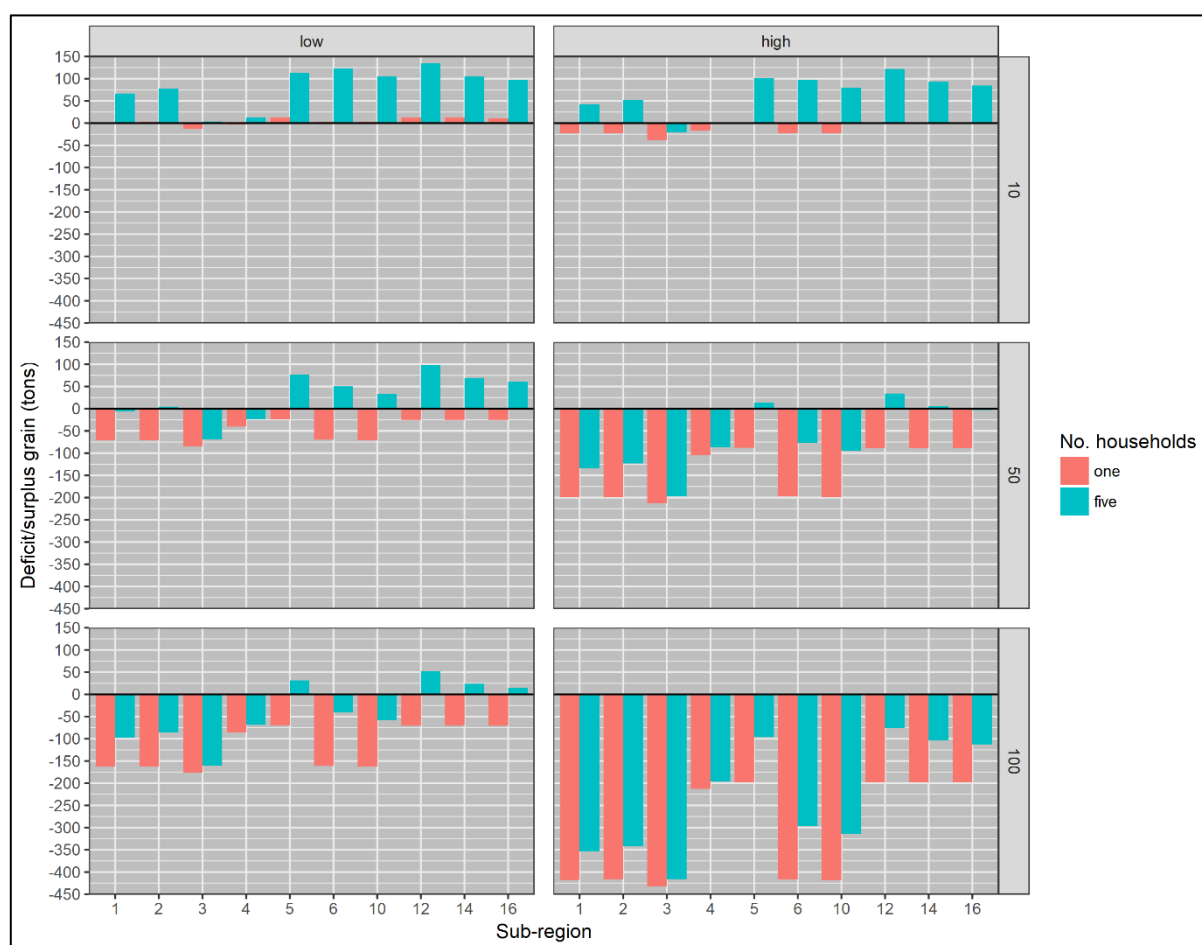
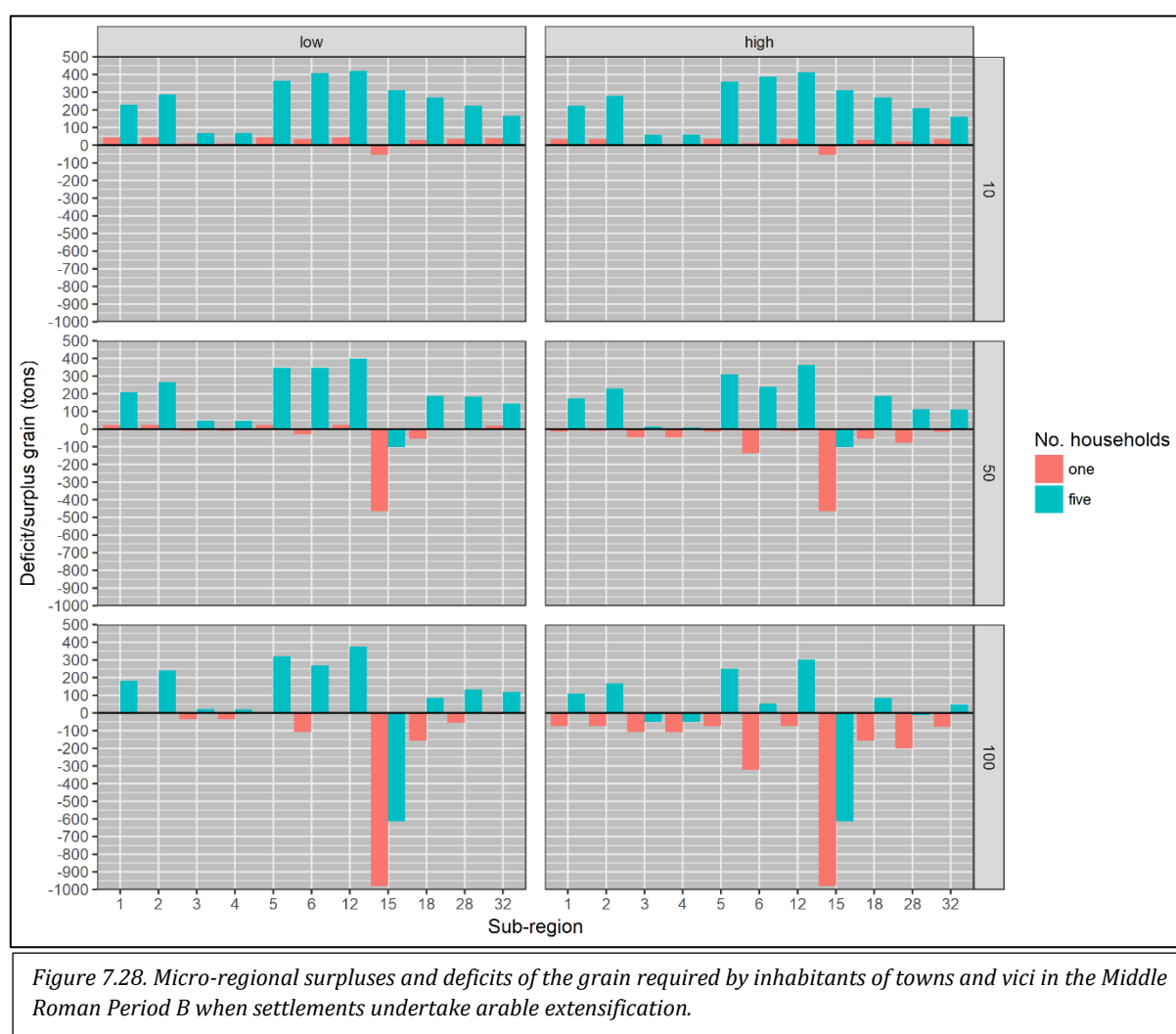
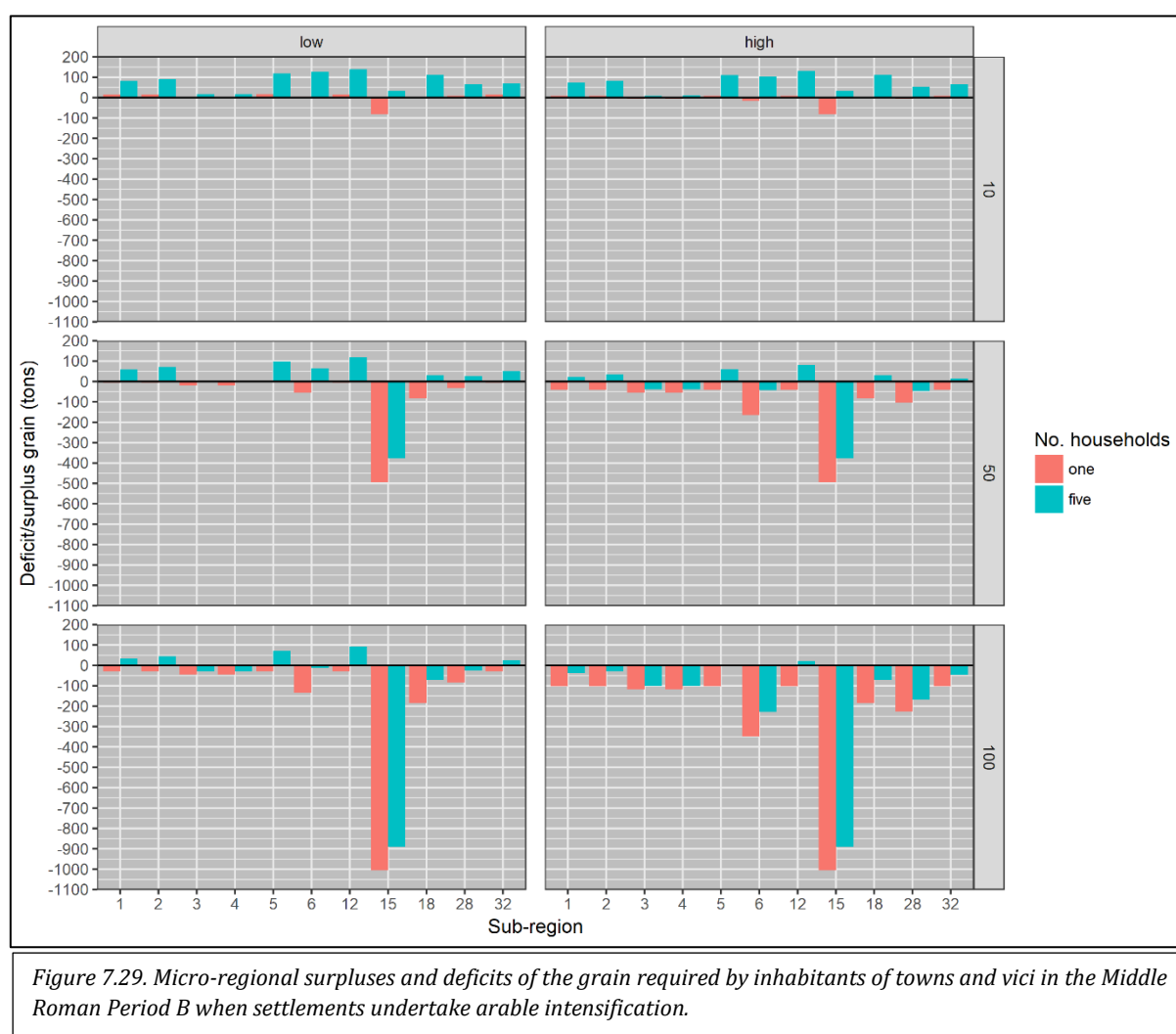


Figure 7.27. Micro-regional surpluses and deficits of the grain required by soldiers in the Middle Roman Period B when settlements undertake arable intensification.





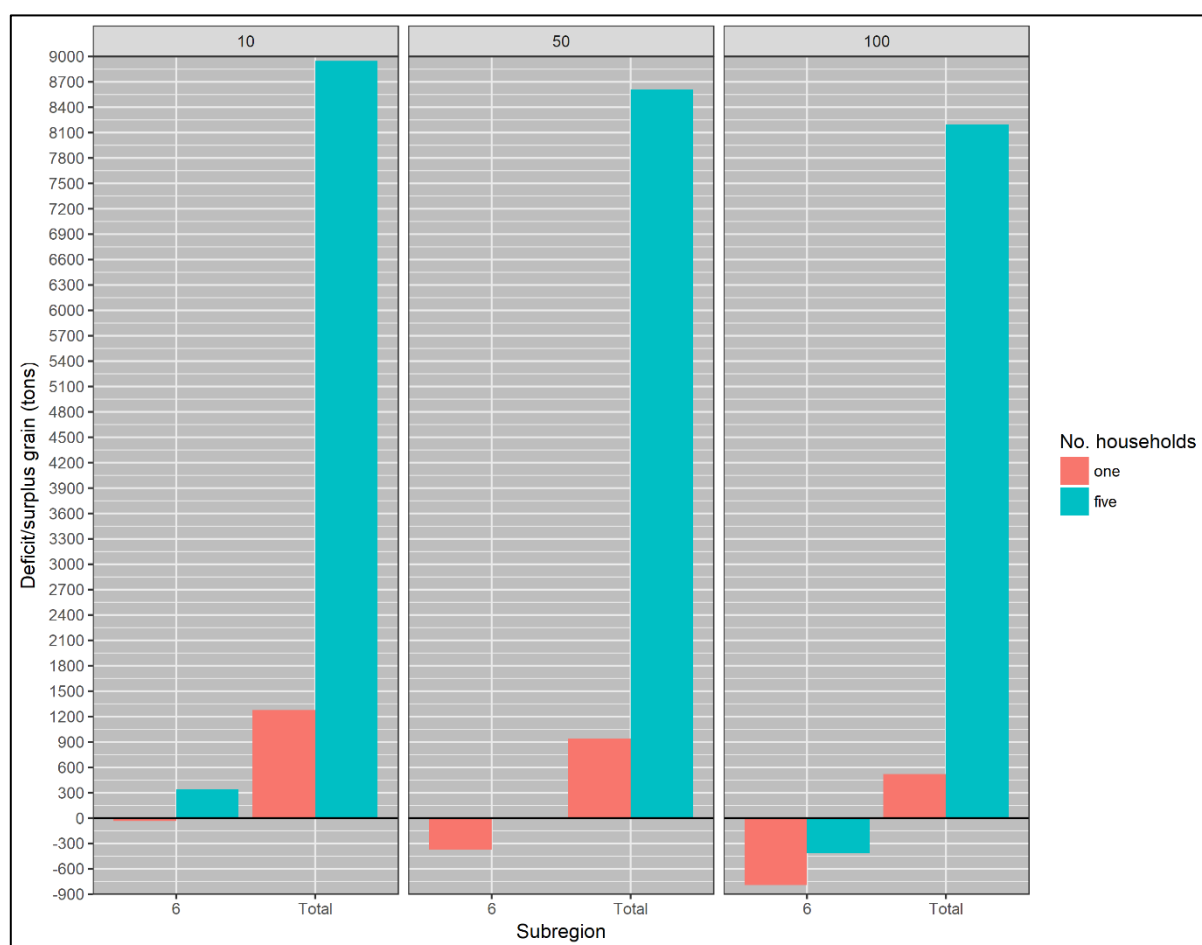


Figure 7.30. Micro and macro-regional surpluses and deficits of the grain required by military equids vici in the Middle Roman Period B when settlements undertake arable extensification.

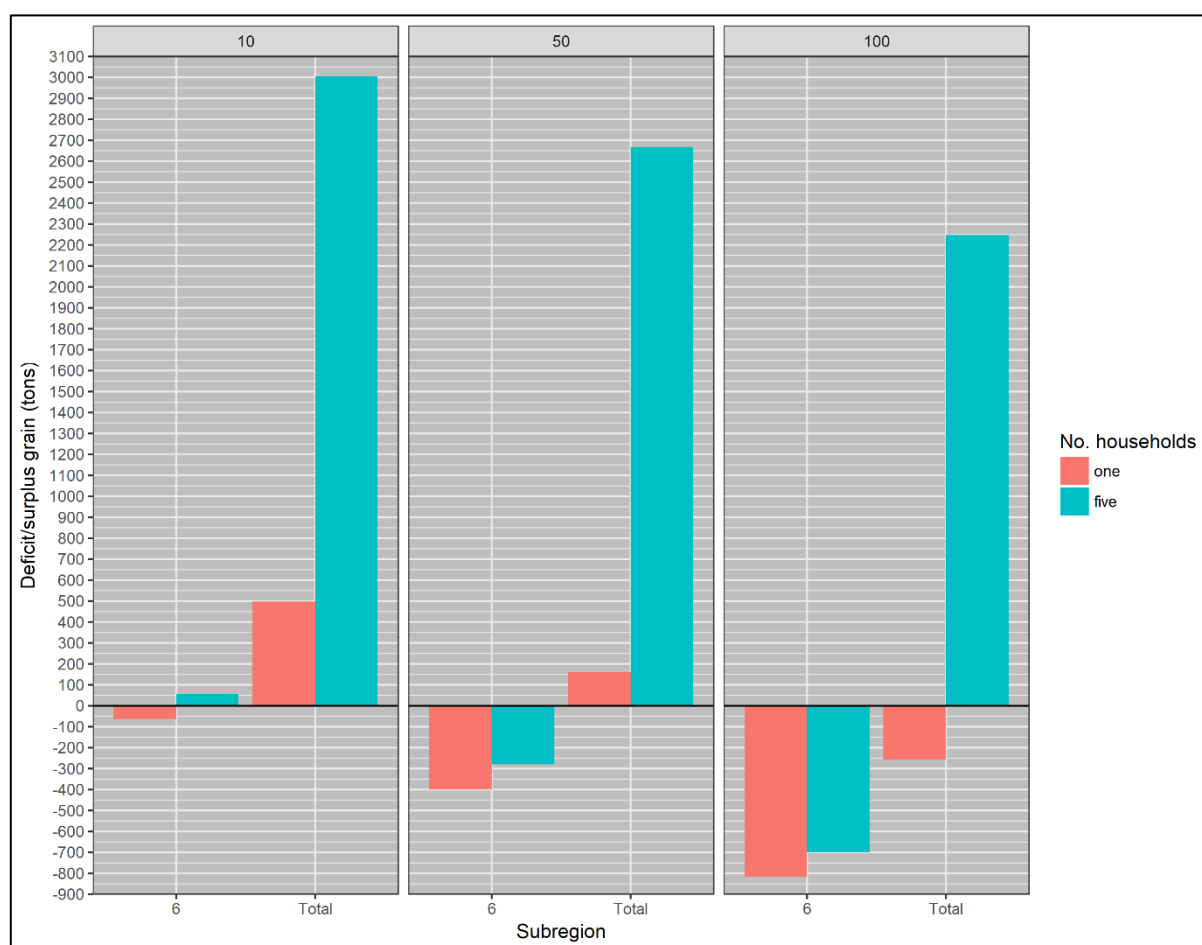


Figure 7.31. Micro and macro-regional surpluses and deficits of the grain required by military equids vici in the Middle Roman Period B when settlements undertake arable intensification.

7.5.1. The Late Iron Age (250-12 BCE)⁶

Only one military settlement is present in the study-region between the years 250 and 12 BCE and then only from 19 BCE: Nijmegen Hunerberg (see table 7.3). It is assumed during this period native agrarian settlements were undertaking subsistence-based agriculture. The total demanded is calculated based on year-round occupation, whereas it was probable that the camp was occupied only seasonally. Results from scenarios with settlements undertaking subsistence-based arable farming and animal husbandry have shown that potential surpluses are small with potential grain supply also very low (see chapter 5). The quantity of surplus grain that is produced by settlements located in sub-region 17 as well as by all settlements located in the study-region is insufficient to supply the assumed two legions that may have occupied this early military settlement in the Dutch *limes* zone (see figure 7.4). This includes those scenarios with sub-regions occupied by large settlements with five households and those scenarios where the proportion of the soldier's diet that was demanded from local settlements was very low. Thus, even if settlements in the direct vicinity have five households, less than 1% of the total grain required by the soldiers at Nijmegen could be supplied by settlements located in the Lower Rhine delta. A macro-regional supply is equally unfeasible. The combined surplus grain produced by all settlements in the Dutch *limes* zone contemporaneous with the early legionary camp at Nijmegen is too small to fulfil the demands of the soldiers located there in all scenarios.

As noted above, surplus grain produced in the Dutch *limes* zone may not have been consumed by human inhabitants of the *castella* or *vici*. Instead, grain could have been used to feed animals attached to these settlements. A possible population of 240 cavalrymen has been assumed for the entire region in this period which were located in the early legionary camp at Nijmegen. This corresponds to 120 cavalrymen per legion and therefore at least 120 horses (the actual number of equids was probably much higher but impossible to estimate). Micro-regional supply by only those settlements located in sub-region 17 is not feasible in any scenario with different sized settlements or different quantities demanded by soldiers (see figure 7.5). Under subsistence-based arable farming, surplus grain produced is too low in this sub-region to supply even 10% of the total fodder required even when the sub-region is occupied by settlements with five households. More scenarios of macro-regional supply are feasible, however. When 10% or less is demanded from local settlements, the combined surplus grain produced by settlements with single households in the Lower Rhine delta is great enough to supply fodder to the legionary camp at Nijmegen (see figure 7.5). For landscapes with settlements with two households, 30% or less can be supplied by native settlements. In scenarios with larger settlements, 40% or less and 70% or less can be supplied in scenarios when landscapes are occupied by settlements with three or five households respectively.

7.5.2. The Early Roman Period (12 BCE-70 CE)

In the first part of the Early Roman Period (12 BCE–25 CE), three *castella* were present in the *limes* region at Arnhem-Meinerswijk (sub-region 14), Nijmegen Kops Plateau (sub-region 17) and Vechten (sub-region 6) (see table 7.3). In most scenarios, the surplus grain available from native agrarian settlements undertaking arable extensification in the three sub-regions with military settlements is sufficient to fulfil the requirements of the estimated number of soldiers present (see figure 7.6). In all scenarios with different estimated demands, the surpluses produced in sub-regions when occupied by settlements with five households are sufficient to fulfil the military demand for grain. In landscapes occupied by settlements with two or three households, deficits have only been calculated in sub-region 6 and 17 when demand is relatively high. Settlement

⁶ Periods used in this study correspond to ARCHIS periods. Therefore although the first military settlement located at Nijmegen is Early Roman, it's short occupation falls within the very end of the Late Iron Age dating used by ARCHIS.

density in sub-region 17 is lower than that in the other two sub-regions which results in a smaller number of settlements emerging from the simulation. Demand from Vechten in sub-region 6 has also been estimated to be twice that from other *castella* in the Dutch *limes* zone given that it housed a double-size cohort. As a result, there are fewer scenarios in which supply on a micro-regional scale is feasible. In scenarios where sub-regions are occupied by settlements with just one household, the potential surplus produced by each household is small enough that in most cases a deficit has been calculated. Only in scenarios with a low demand from military settlements do settlements with one household in each sub-region produce enough grain to supply *castella* located in their sub-region. An alternative mechanism of supply of consumer-only settlements in the Dutch *limes* zone is via a macro-regional scale. The total military population in the Dutch *limes* zone during the Early Roman Period A is comparatively small and thus the total surplus grain produced in the entire Dutch *limes* zone in all scenarios is sufficient to fulfil the demand of all soldiers present in the study region when settlements undertake arable extensification.

Settlements undertaking extensification produce on average greater quantities of surplus grain than those undertaking arable intensification. When settlements practice arable intensification, the pattern of surpluses and deficits among different sub-regions and scenarios are different (see figure 7.7). In general, there are fewer scenarios where supply on a micro-regional basis is feasible. Demand from *castella* needs to be lower when settlements undertake arable intensification for there to be sufficient grain for soldiers present compared to scenarios undertaking arable extensification. Furthermore, even in landscapes with settlements with five households, when there is a high demand from military settlements, surplus grain produced in each sub-region is insufficient to supply local soldiers with enough grain. Despite a micro-regional supply mechanism not being feasible in many more scenarios when settlements undertake intensification compared to scenarios when settlements undertake arable extensification, supply on a macro-regional basis remains feasible in most cases (see figures 7.8 & 7.9). Only when landscapes are occupied by settlements with single households are deficits calculated and then only when estimated demand from military settlements is at its highest i.e. when the number of soldiers estimated uses higher estimates of c. 600 soldiers per castellum and when inhabitants derive 100% of the grain required from locally produced surplus grain.

In the Early Roman Period A (12 BCE – 25 CE) the only evidence for a town or *vicus* is in Nijmegen (sub-region 15). On a micro-regional scale, when the sub-region is occupied by small settlements undertaking arable extensification, deficits occur in most scenarios except when demand is very low (see figure 7.10). In scenarios with larger settlements, greater demand for grain can be met by local agrarian settlements. A similar pattern can be observed when settlements undertake arable intensification (see figure 7.11). However, deficits are larger and surpluses are smaller on this micro-regional scale because surplus grain produced per settlement is lower. With only one *vicus* present in the *limes* zone during the Early Roman Period A, it is not surprising that the total surplus grain produced by all settlements in the Lower Rhine delta is in excess of the total grain demanded in all scenarios. Although the surpluses are lower when settlements undertake intensification or are smaller and are also lower when demand from *vici* is high, deficits have not been calculated (see figures 7.12 & 7.13).

During the Early Roman Period B (25–70 CE), the population of soldiers in the Dutch *limes* zone increases substantially from the preceding period (see table 7.8). Total demand of food from the military increased in the region overall. In sub-region 6 which already had a military presence at Vechten, micro-regional demand increases further with the development of a *castellum* at Utrecht. Although there is an overall increase in demand for grain from periods A to B in the Early Roman Period, settlement densities also increase in approximately a third of sub-regions and there is no change in the remaining sub-regions (see table 7.2). As a result, the quantities of

surplus grain available from the whole region increases as does the quantities available in several sub-regions. Micro-regional supply in scenarios where settlements with two to five households undertake arable extensification is feasible in a majority of sub-regions provided that sub-regional demand from military settlements is not in the highest possible range of estimates (see figure 7.14). Naturally, sub-regional supply in sub-region 4 is infeasible in all scenarios as no settlements exist in the data-set for this period. Furthermore, the very low settlement density on sub-region 3 in this period means that the amount of surplus grain produced is small even when settlements possess five households. Micro-regional supply in this sub-region is therefore infeasible in almost all scenarios. For settlements with one household, surplus grain produced remains low in each sub-region meaning that micro-regional supply is only feasible when military demand from native settlements is very low.

In the Early Roman Period B, because surplus grain produced is significantly lower than produced when settlements undertake arable extensification, there are also fewer scenarios when a micro-regional supply mechanism is feasible (see figure 7.15). Micro-regional supply remains infeasible in sub-regions 3 and 4 on account of settlement densities here. Surplus produced by settlements with three or five households, are, on average, sufficient to fulfil the grain demand by soldiers in the other sub-regions unless demand is very high. When sub-regions are occupied by settlements with two households, the quantity of surplus grain produced in each sub-region can be large enough to supply military settlements by local agrarian settlements if demand from soldiers is equal to or less than 30, 60 or 90% of the total grain required depending on the estimate for the settlement's population of soldiers. Unless estimated demand is very low, surplus grain produced in each sub-region with a military settlement is not able to meet the demands of soldiers.

Similar to the preceding period, settlements in the whole study-region can, in most scenarios, produce sufficient surplus grain to meet or exceed the total estimated demand of all military settlements in the Dutch *limes* zone (see figures 7.8 & 7.9). When settlements undertake arable extensification, only when demand from local settlements exceeds 70% of the total demand and the estimated population uses traditional approximations of cohort size can settlements with one household be unable to produce enough surplus grain. When settlements undertake arable intensification, macro-regional grain production is insufficient only in scenarios when estimated demand is high.

The emergence of Forum Hadriani (Voorburg) and a settlement at Cuijk increased the population of towns and *vici* in the Early Roman Period B (see tables 7.3 & 7.9). Despite this increase in urban populations in some sub-regions, scenarios of a micro-regional scale of supply are feasible when demand from towns and *vici* is low and supply from local rural settlements is high (see figures 7.16 & 7.17). When settlements undertaken arable extensification and possess only one household, estimated demand must be very low for enough surplus grain to be supplied. When settlements possess five households, a micro-regional supply is feasible in all scenarios when settlements practice arable extensification. In scenarios when settlements undertake arable intensification the pattern of surpluses and deficits is different (figures 7.12 & 7.13). A micro-regional scale of supply is infeasible in most scenarios when settlements are small and practice arable intensification. Demand in sub-regions outstrips supply except in scenarios when very little surplus grain is demand: c. 10% of the total required by the inhabitants of the towns and *vici*. Total surplus grain produced in each sub-region by large settlements undertaking arable intensification results in smaller surpluses in scenarios when micro-regional supply is feasible. Furthermore, in contrast to scenarios when settlements undertake arable extensification, deficits are calculated for some sub-regions (15 and 32) when demand is high i.e. a high population estimate per settlement is assumed and 100% of the grain required is demanded. A macro-

regional supply scale is, once again, feasible in more scenarios (see figures 7.10 & 7.11). Given that total grain demand is low as only three towns or *vici* are in the data-set for this period, a macro-regional scale of supply is feasible in all scenarios. The total surplus grain produced in the whole *limes* zone is greater than the total grain demanded, even when 100% of grain is demanded.

In the Early Roman Period B, the estimated demand for fodder comes from the estimated 240 cavalrymen from the possible double cohort inhabiting Vechten (see table 7.11). Settlements occupying the same sub-region can produce enough grain to fulfil 100% of the fodder demand when these settlements have five households and undertake arable extensification (see figure 7.18). However, in scenarios with smaller settlements only a minor proportion of the total demand can be fulfilled by native agrarian settlements. In contrast, settlements undertaking arable intensification can not supply military settlements on a micro-regional scale (see figure 7.19). Demand from cavalry in sub-region 6 can not exceed 40% of the total amount required if the local settlements have three or five households and not even 10% of the total amount can be supplied by smaller settlements. Conversely, macro-regional supply of fodder is feasible in all scenarios. The total demand from the estimated number of cavalrymen for fodder can be met by settlements of all sizes in the Dutch *limes* zone whether extensification or intensification is undertaken.

7.5.3. The Middle Roman Period (70-270 CE)

The number of military settlements including *castella* and *castra* increases again from the Early Roman Period B to the Middle Roman Period A (see table 7.3). In addition, the military settlement at Nijmegen developed from a smaller *castellum* housing a cohort to a *castra* where a legion was present. Calculated settlement densities increase in most sub-regions also although in sub-regions 5, 13, 16, 28, 30 and 32 there is a small decline in the calculated settlement density (see table 7.2). Overall therefore there is both an increase in demand from military settlements (see table 7.3), and a corresponding increase in potential supply. This potential increased supply contemporaneous with an increased demand is reflected by the results. The results show little change in the pattern of surpluses and deficits calculated within sub-regions when a micro-regional supply mechanism is assumed. This is true of scenarios where settlements undertake intensification and extensification (see figures 7.20 & 7.21). In the former scenarios, demand must be relatively low for native agrarian settlements to produce enough surplus grain to match demand and for smaller settlements micro-regional supply is infeasible except in scenarios with very low demands. In the latter scenarios, settlements undertaking extensification can supply greater quantities of grain to meet higher demands although for settlements with single households, demand cannot exceed between 20 and 40%, depending on estimates for military population per military settlement, before potential deficits are calculated. A significant difference is however micro-regional supply in sub-region 17. The large increase in demand caused by the presence of a legion rather than a cohort in this sub-region, invariably can not be met by settlements when arable intensification is undertaken. Micro-regional supply of the *castrum* at Nijmegen is feasible when settlements undertake extensification but only if the sub-region is occupied by large settlements and demand by soldiers from local agrarian settlements is 10% or less of the total required.

Macro-regional supply is feasible in more scenarios (see figures 7.8 & 7.9). Notably, when settlements with two to five households undertake extensification, farms in the Middle Roman Period A can produce enough grain for soldiers regardless of the proportion of the total amount required that is demanded from local agrarian settlements. Only for scenarios with settlements comprising a single household are deficits calculated. For scenarios where settlements undertake arable intensification the pattern of surpluses and deficits is different. Single household

settlements can not supply more than 10 to 20% of the total amount of grain required by soldiers present in the Dutch *limes* zone at this time. Settlements with two households can not supply more than 40-60% and settlements with three households can supply between 40 and 90% depending on the estimated number of soldiers present. Even in scenarios where settlements have five households, deficits are calculated when very high demands from military settlements are assumed.

Total demand for grain declines in the Middle Roman Period B and decreases significantly with the departure of the *X Legio Gemina* from Nijmegen. Apart from the mini-*castellum* at Ockenburgh, whose population is not considered, no new military settlements develop in the Dutch *limes* zone during this period (see table 7.3). Settlement densities remain stable for most sub-regions however a small minority experience a decline in settlement density (see table 7.2). There is therefore a decline in local supply also, however, decline in demand is greater. As a result, there are no major changes in scenarios where micro-regional supply is feasible compared with the previous period both when settlements undertake arable intensification or extensification. Micro-regional supply remains infeasible in most sub-regions unless settlements are large or unless demand is relatively low (see figure 7.26). Micro-regional supply of *castella* located in the central peat region (sub-regions 3 and 4) is, by virtue of the sparse occupation of rural agrarian settlements, particularly infeasible even for scenarios with large settlements. Micro-regional supply in scenarios where settlements undertake arable intensification remains unlikely, with deficits calculated except in scenarios with very low demand and very high supply (see figure 7.27).

As a result of the decrease in total demand in the Dutch *limes* zone for grain in the Middle Roman Period B there is an overall increase in the number of scenarios where macro-regional supply is feasible. When settlements undertake arable extensification, the sum total of grain produced by settlements with two to five households in the whole study-region is great enough to fulfil 100% of the total demand from military settlements (see figure 7.8). For settlements with just one household, production of surplus grain is sufficient enough to fulfil demand in most scenarios except those where demand is very high e.g. when demand exceeds 70% of the total required and when the estimated number of soldiers per settlement uses traditional estimates of c. 600 men per cohort. When settlements undertake arable intensification, there are fewer scenarios when enough grain is produced for soldiers particularly when landscapes are occupied by settlements with one or two households compared with the preceding period (see figure 7.9).

In the Middle Roman Period A, the total number of towns and *vici* increases significantly with the emergence of *vici* attached to *castella* emerging from 70 CE and reaching its maximum in the Middle Roman Period B (see table 7.2). In both periods, the demand for surplus grain is greater than in the preceding periods. In most sub-regions, local supply of grain in scenarios when settlements are small is too little to fulfil the demand from towns and *vici* (see figure 7.22 & 7.29). Except when demand is very small because the population estimate is low and the proportion of the total grain needed that is demanded from local settlements is low, is there sufficient locally produced surplus grain. When settlements are larger, deficits are not calculated unless when demand is very high. The results show that for the much larger estimated population in *civitas* capital at Nijmegen, local supply would have been more problematic with deficits calculated in scenarios with lower demands. When settlements undertake intensification, the surplus grain produced in each sub-region is insufficient to meet the demands of the towns and *vici* unless only 10% is demanded from local sources in scenarios with small settlements (see figures 7.23 & 7.30). A greater proportion can be demand from larger rural settlements with five households but cannot exceed 50% when population estimates are high before deficits are calculated and less than 100% when population estimates per settlement are low.

Assuming local supply was undertaken on a macro-regional scale, the results show that for both the Middle Roman Period A and B this mechanism was feasible in more scenarios. The total grain required by all towns and *vici* in the *limes* zone can not be met by the total surplus grain produced by all small settlements present in the region in these periods (see figures 7.9 & 7.10). However, 50% can be fulfilled when small settlements undertake extensification, and 10% can be fulfilled when settlements undertake arable intensification. When sub-regions are occupied by larger settlements with five households, deficits in any scenario are not calculated. However, the total surpluses left after local settlements have supplied towns and *vici* are much lower when settlements undertake arable intensification. The results confirm that local supply is more feasible therefore on a macro-regional scale for towns and *vici* in these periods also.

The estimated number of cavalrymen is highest in the Middle Roman Period A with 120 cavalrymen attached to the legion at Nijmegen and up to 620 in sub-region 6 (see table 7.11). The results show that micro-regional supply remains unlikely in both scenarios where settlements undertake extensification or intensification (see figures 7.24 & 7.25). For the latter, it is infeasible for all but a few scenarios. Only when sub-regions are occupied by settlements with five households and 20% or less of the total fodder required is demanded from native agrarian settlements is there enough surplus grain. Whilst there are more cases where micro-regional supply is feasible when settlements undertake arable extensification, it remains unlikely especially for settlements with one or two households. Conversely, the results show that macro-regional supply is more feasible. Grain fodder produced in the entire Dutch *limes* zone by settlements in the Middle Roman Period A practicing arable extensification is sufficient to fulfil the full demand of the estimated number of cavalrymen regardless of settlement size. If settlements undertake intensification, macro-regional supply is insufficient only for settlements with single households when demand reaches 50% of the total amount required.

In the Middle Roman Period B, demand for fodder reduces somewhat with the estimated number of cavalrymen calculated as 500 from the *ala* stationed at Vechten (see table 7.11). The difference in estimated populations does not change significantly the pattern of surpluses and deficits of grain fodder among the different scenarios of demand and supply, however. Macro-regional supply remains feasible in more scenarios and in scenarios when settlements undertake arable intensification (see figure 7.31). In addition, the maximum proportion of the total grain fodder required that can be supplied by settlements with one household undertaking arable intensification increases to 60%. Micro-regional supply remains infeasible when settlements undertake intensification in almost all scenarios and demand must be low for settlements undertaking extensification to be able to supply grain fodder on a micro-regional basis. For settlements with one household micro-regional supply is not feasible in any scenario where settlements practice extensification.

7.6. Surplus and deficits: the feasibility of local supply to military settlements and *vici*

Comparisons of estimated demand of food from soldiers, inhabitants of *vici* and military animals in the Dutch *limes* zone from the beginning of Roman presence in the region until the collapse of the *limes* with the potential surpluses of grain and animal products that settlements produced in different scenarios have shown several scenarios in which local supply was feasible and where local supply was not feasible. Grain grown in the Dutch *limes* zone during the Roman period by native agrarian settlements was dominated by six-row barley (*Hordeum vulgare*) and emmer wheat (*Triticum dicoccon*) neither of which are commonly associated with the Roman military diet. The consumption of emmer wheat is not improbable. Whilst the consumption of barley in forms such as porridge has not been dismissed outright, it is more realistic that locally produced

emmer wheat was meant for humans and barley for animals. ROMFARMS does not distinguish between the two species as both have similar yields and calorific content. Archaeobotanical evidence from rural settlements shows a mix of different species were grown, indicating that settlements may have cultivated both grain sorts but perhaps for different consumers. Calculations based on scenarios where all settlements are involved in the supply of both animals and humans or in scenarios where some settlements grow barley for animal fodder, and some grow emmer for human consumption are needed also. To do so in ROMFARMS would require the simulation of different arable farming strategies such as multiple croppings of different species each year or mixed croppings where different grain sorts are cultivated simultaneously. Such strategies have yet to be implemented. The calculations from ROMFARMS are based, therefore, on a mono-culture where all settlements cultivate either barley or emmer wheat with the results based on settlements supplying either humans or animals with their surpluses, but not both.

Owing to a number of uncertainties in the data-set used as well as in assumptions used in ROMFARMS, the results of simulation may not accurately be representative of supply and demand of grain in the Dutch *limes* zone during the Roman period. The results are true of the situation of the past only as far as ROMFARMS accurately emulates agriculture in the Dutch *limes* zone. As noted above, ROMFARMS simulates landscapes as occupied homogeneously with settlements all possessing the same number of households in each sub-region. By doing so the possible range of values is calculated. Settlements in sub-regions also undertake the same agricultural strategy. Therefore, calculations use results where all settlements undertake arable intensification or extensification. Additionally, the results have come from simulations where all settlements undertake only extensive surplus animal husbandry. It was probable that different agricultural strategies were undertaken simultaneously by different settlements inhabiting the same landscape. Uncertainties in the data-set of military settlements and *vici* affect the robustness of estimated demand in each sub-region. Over- and underestimates of demand can alter the patterns where surpluses or deficits would occur in both sub-regions and the entire Dutch *limes* zone. In particular, it is likely that estimates of animals attached to military settlements such as equids is vastly underestimated but with the current state of knowledge the number of animals is impossible to estimate with any certainty.

Regarding grain supply for human consumption, the results show that a macro-regional supply mechanism was more feasible than supply on a micro-regional basis. This is true only for Early Roman and Middle Roman periods, however. The results have shown that local supply of grain for human consumption by settlements undertaking subsistence-farming is not possible. Therefore, the inhabitants of the early legionary camp in Nijmegen, would have been unable to rely on native agrarian settlements for grain. In some sub-regions, the numbers of settlements that emerge from the simulation are insufficient to produce sufficient grain to meet the demands of local soldiers and non-agrarian civilians unless demand is relatively small, or landscapes are occupied by very large settlements. Simulations with a homogeneous size of settlement have developed a possible range of potential surplus grain, however landscapes occupied only by large settlements with three to five households are unrealistic and not corroborated by archaeological evidence. Whilst large settlements are present in the study region, archaeological evidence indicates the majority are small comprising just one or two households (see Vossen 2003; van Dinter *et al.* 2014). If, then, it is assumed that landscapes with smaller settlements are more realistic, the results in these scenarios point to a macro-regional supply mechanism being more able to supply consumer-only settlements with sufficient food. A macro-regional supply network for grain is made more likely also given the lack of uniformity in supply from each of the sub-regions with some sub-regions more densely populated than others and producing more surplus grain than others. A macro-regional supply mechanism would also appear to be more able to

respond to changes in demand throughout the Roman period. In particular, the significant increase in military population and therefore demand for grain with the stationing of a legion at Nijmegen could be met from a macro-regional supply mechanism but is infeasible in scenarios with micro-regional supply.

De Kleijn *et al.* (2016; 2018) rejected van Dinter *et al.*'s (2014) calculations that 50% of the total cereals demanded by Roman military and *vici* inhabitants could have been produced in both the Early and Middle Roman Periods. De Kleijn's *et al.*'s analysis of landscape capacity argued that whilst possible for the Early Roman period, it was not possible for local settlements to produce enough grain to fulfil 50% of the total demand in the Dutch *limes* zone. The results from ROMFARMS indicate that at least 50% can be supplied by rural agrarian settlements in both the Early and Middle Roman Periods via a macro-regional basis as van Dinter *et al.* (2014) calculated. Substantially, less can be supplied by settlements undertaking intensification, however. The discrepancy may be from the number of settlements estimated by de Kleijn *et al.* (*in press*) that are lower than those in the data-set used by ROMFARMS given that the study region used by ROMFARMS is significantly larger. Total supply is therefore greater in calculations used by ROMFARMS than by de Kleijn *et al.*'s (2016; 2018) study. In addition, land use per settlement according to the results of simulation with ROMFARMS is lower than the assumptions made by van Dinter *et al.* (2014) which have been used by de Kleijn *et al.* (2016; 2018).

The number of military animals in the study-region in the Roman period are very uncertain and the estimated population of equids is probably only a very small proportion of the total number. Nevertheless, the results show that for both the Early Roman and Middle Roman Period a macro-regional scale of supply is more feasible than a micro-regional scale. In almost all scenarios, settlements located in those sub-regions with cavalrymen are unable to produce sufficient fodder grain. In contrast, the combined total grain produced in both scenarios where settlements undertake intensification and extensification is sufficient to fulfil the demands of cavalry horses on a macro-regional scale. As the estimated population of equids in the region is undoubtedly under-representative of the probable population, it can not be said with certainty that native agrarian settlements could supply fodder grain for all equids in the Dutch *limes* zone. However, given that the supply on a macro-regional scale can supply more grain fodder than needed, many more military animals could be supplied by the simulated number of settlements, particularly when settlements undertake arable extensification.

The production of surplus fodder grain for cavalry in the Dutch *limes* zone is considered briefly by van Dinter *et al.* (2014). It is also considered by Vossen & Groot (2009) for the eastern area of the *limes* zone in the *civitas Batavorum*. For van Dinter *et al.* (2014), local supply of sufficient fodder grain was not possible. Settlements in the *civitas Batavorum* could have supplied enough fodder grain according to calculations by Vossen & Groot (2009) however. The number of settlements in the study-region used for this research is significantly greater than that used by van Dinter *et al.* (2014) and therefore supply is greater. The results from ROMFARMS do not necessarily reject the conclusions made by van Dinter *et al.* (2014) but indicate the importance of a macro-regional supply mechanism using grain produced in a region larger than used by their study.

A final possible way in which local settlements supplied *castella* and *vici* with food is via surplus production of meat. Van Dinter *et al.* (2014) were sceptical of the possibility for native agrarian settlements to engage in extensive surplus animal husbandry owing to labour limitations as opposed to limitations for suitable land. The results from ROMFARMS offer an alternative assessment of the potential for surplus production of animal products in the region, however. The total number of animals that can be kept by settlements as expressed by numbers of herds is more

than required by each settlement indicating the possibility for surplus production. Supply from local settlements of animal products relies on the inclusion of milk as an important product that is conspicuously absent in most discussions of the agricultural economy of the Dutch *limes* region. Fewer calories would be available for consumer-only settlements if milk, or derived products, were not supplied. The likelihood of milk as a raw product being supplied in the past is slim, however. The results suggest a greater role for dairy products, most probably cheese, than previously considered, therefore.

The impact on land usage by settlements undertaking extensive surplus animal husbandry is great, with all available potential meadow and pasture land used. The number of animals kept by settlements undertaking surplus animal husbandry as simulated would be very great too which may not be reflected in the archaeological evidence, however. As van Dinter *et al.* (2014) argued, there is no evidence for increases in stable size for example that would permit settlements to keep larger herds within the settlement. The implication for this agricultural strategy is that animals were kept away from the settlement throughout the year. Of course, extensive surplus animal husbandry as simulated shows the extreme upper limit of potential production of animal products. Given that the results have shown more animal products than necessary can be produced by extensive surplus animal husbandry, some of the maximum number of animals that can be kept by settlements in each sub-region are superfluous. It can be envisaged that fewer animals than calculated would still permit native agrarian settlements to supply military and civilian settlements with animal-derived calories.

A macro-regional supply mechanism in the Early and Middle Roman periods would have required a sophisticated supply network in which grain would need to be moved around the *limes* region to consumer-only settlements that required it. Understanding how this could be achieved is beyond the remit of this research, However, a combination of the approaches undertaken by Groenhuijzen & Verhagen (2015, 2016, 2017) and the results from ROMFARMS could produce new hypotheses regarding the how surpluses were moved across the Lower Rhine delta. As Groenhuijzen & Verhagen (2017) noted, it is unlikely that grain from one side of the Dutch *limes* zone would be moved to the other. The most realistic supply network lies towards the macro-regional scale in the range from the micro- and macro-regional scale. The development of different transport networks can help to investigate where in the range investigated what the most appropriate scale is. It may have been that for a macro-regional supply mechanism to function, native farmers would be required to transport grain themselves throughout the Dutch *limes* zone, or, more probable, transport grain to local hubs or depots. Stone-built rural settlements have been posited by Vos (2009) as having an important part in the socio-economic structure of the Dutch *limes* zone and network analysis by Groenhuijzen & Verhagen (2015) has shown that some stone-built settlements occupy important bottleneck sites. It is possible that stone-built settlements served as important sites for the accumulation of locally produced surplus grain to be transferred throughout the region therefore (see also Groenhuijzen 2018). Archaeological evidence has also indicated the increase in size of granaries with some granaries able to store more grain than the estimated production capacity of the settlement (see Groot *et al.* 2009). Whilst the investigators suggested that the large granaries at Tiel-Passewaaij and Wijk bij Duurstede could have been used to store fodder as well as grain for human consumption, it is not inconceivable that they also served as depots for surplus grain produced by other settlements in the region. It is unlikely that a macro-regional supply network could have developed with the immediate arrival of the Roman army in the region, however. Nor is there any implication that a supra-regional supply network was required particularly for the import of grain for human consumption. The import of grain still occurred throughout the Roman period. Cereal spectra in military settlements in the Early Roman Period point to plants from both sides of the Rhine being

supplied by native settlements. By the Middle Roman Period plants typical of settlements north of the Rhine disappeared from both *castella* and *vici* which Kooistra (2009) suggests indicates the possibility of the Rhine forming a closed border for import of food plants. Settlements continued to be supplied by settlements even further afield, however. The potential for ROMFARMS to combine both an agent-based model of agriculture with simulations of trade and transport networks should be investigated to gauge further the feasibility of different mechanisms of supply from native agrarian settlements to consumer-only settlements such as *castella* and *vici*. In addition, the results say nothing of the way grain, animal products and fodder were demanded from local settlements.

As supply from rural settlements is determined by both strategy and the number of settlements, the robustness of the calculated supply is dependent on the robustness of the simulated number of settlements in each sub-region. ROMFARMS utilises settlement density rather than absolute number of settlements which incorporates stochasticity in this sub-model. The assumed settlement density and the in-built rules of the demographic sub-model have a significant impact on the number of settlements, whereby the creation and removal of settlements is determined by the demographic rules and settlement density provides the upper limit of the number of settlements in each sub-region. The demographic sub-model used in this model is problematic and an oversimplification of demographic processes in the Dutch *limes* zone, however. Furthermore, settlement densities are calculated using the data-set of rural settlements known from the archaeological record whose dating, as discussed above, is often uncertain (see also Verhagen *et al.* 2016b). It is very unlikely that the number of settlements that emerge from the simulation represent realistically the number of settlements present at any time in the Dutch *limes* zone during the Roman period. This means that the estimated quantities of food produced are probably lower than what were actually produced in the past.

8. Synthesis

8.1. Framing the debate: agricultural productivity and surplus production in the Dutch Roman *limes* zone

Within studies of the agricultural economy of the Dutch Roman *limes* zone, substantial effort has been spent on the debate concerning surplus production in the region. Archaeological research has focused on the evidence for and against the possibility for native rural settlements in the region to have produced a surplus of grain or animals for military settlements and *vici* in the region. Since the initial pessimistic interpretations of agricultural productivity in the region, research has found evidence in archaeobotanical, zooarchaeological and other archaeological data that points to surplus production in the region as not only possible but having taken place during the Roman occupation of the region (see chapter 2).

In light of this, as a starting point for this research, the hypothesis that surplus production in the Dutch *lime* zone by local native farmers was possible was accepted. It was accepted in addition that both land and labour were limiting factors of agricultural productivity. From previous research relating to surplus production in the study region, several possible strategies of surplus production can be inferred: extensive agricultural strategies, intensive agricultural strategies and specialist strategies. Extensive agricultural strategies were assumed by Kooistra (1996) and van Dinter *et al.* (2014) for example, whereby greater areas of arable land were cultivated but with no change from the pre-Roman Late Iron Age in how arable land was cultivated. In addition, it can be inferred that van Dinter *et al.* (2014) also assumed an extensive animal husbandry strategy whereby more animals are kept by animals to increase yield and therefore the land and costs required for animals increase. In an analysis of the faunal assemblages, Groot (2008b; 2016; see also Kooistra & Groot 2009) interpreted the increasing age of cattle at slaughter as indicative of a role within arable farming with manure and traction becoming important products. Accordingly, predominantly in the eastern part of the Dutch *limes* zone, zooarchaeological evidence implies an intensive arable farming strategy. Lastly, specialised horse-breeding has been proposed as a form of surplus production in the study region. High percentages of horse bone found in rural settlements, particularly in the east (Groot & Deschler-Erb 2015), and the lack of horse consumption (see Lauwerier 1988; also Lauwerier 1999; Lauwerier & Robeerst 2001) indicates the possible surplus production of horses to fulfil the significant demands of the Roman army occupying the *limes* zone.

These possible methods of surplus production in the *limes* region have been interpreted from the archaeological record but, except for extensive agricultural strategies, the effects of these strategies on land and labour costs are missing. Furthermore, there is little or no discussion of how the availability of labour limited agricultural productivity in the region for all possible strategies of surplus production. The importance of land and labour within agriculture, denoted factors of production within classical and neoclassical economics, is undoubted and a discussion of the different strategies of agricultural production must include an explicit analysis of the relative importance of land and labour as limiting factors to better understand the feasibility of different surplus production strategies being undertaken. In addition, as a departure from static landscape capacity models, the simulation of the agriculture of the region as a dynamic process involving stochastic variables (random distribution of resources and fluctuating yields) was necessary.

8.2. Developing the tool

8.2.1. ROMFARMS: an agent-based model of agriculture in the Dutch *limes* zone

A simulation of the agriculture undertaken by rural native settlements of the Dutch *limes* zone in the pre-Roman Late Iron Age and the Roman period was developed in NetLogo (v. 6.0.2, Wilensky

1999). It was used to simulate the entire agricultural year via its tasks: arable farming, animal husbandry and wood collection. System dynamics of settlement population dynamics and animal herd dynamics were combined with an agent-based model to explore the implications of different agricultural strategies on labour and land costs under both subsistence-based farming and surplus agricultural production. Multiple scenarios of agriculture strategies were simulated to discover possible ways the local community could produce a surplus of grain, animal products or horse, and reject those scenarios where the availability of land or labour suggests strategies were infeasible. The simulation model draws upon archaeological research from the Dutch *limes* zone, archaeological and historical economic studies from analogous ancient agricultural societies, and other domain knowledge such as agronomics and ethnography. Parameters using a range of possible values were incorporated where uncertainties remained in the agricultural record e.g. the frequency of fuel collection, or the proportion of the diet of inhabitants that was grain-derived.

8.2.2. Modelled processes

The model relies on several sub-processes which have been discussed in more detail in both chapter 4. They are discussed here briefly with comparisons made with the current state of the art.

8.2.2.1. Settlement demography

The agricultural production unit in the model is the settlement, comprised one or multiple households. A system dynamics model of settlement demography was developed combined with an agent-based modelling simulating marriage, establishment of new settlements and migration. This generates synthetic populations of settlements from where they derive their labour supply. The synthetic population is divided between the “strong” and “weak” workforces (the former comprised of adult men and women, and the latter comprising adolescents and the elderly) and children unable to work (after Danielisová & Štekerová 2015). The model of settlement demography relies on historic data of mortality and fertility rates derived from the Model West Level 3 Female life table (Coale & Demeny 1996) and Coale & Trussel (1978). Probability of death per year was calculated, crudely, from mortalities of five-year age cohorts.

In contrast to demographic models developed by Machálek *et al.* (2012) or Verhagen *et al.* (2016a) for example, the sub-model used in this simulation does not incorporate more complex rules regarding life events such as those governing marriage in Verhagen *et al.* (2016a). In addition, the sub-model produces synthetic populations with stable population growth only using mortality and fertility rates from one life table. More sophisticated models have applied assumptions from multiple life tables (e.g. Verhagen *et al.* 2016a) and used synthetic populations under different demographic profiles: stable, expanding and decline (see Danielisová & Štekerová 2015). Recruitment has not been considered either (cf. Verhagen *et al.* 2016a).

8.2.2.2. Arable farming

An agent-based sub-model of arable farming was included wherein settlements cultivate grain using different behavioural rules associated with three arable strategies: subsistence-based arable farming, extensification, or intensification. Harvests each year fluctuate randomly simulating the effect of climatic factors on yields. Under subsistence-based arable farming,

settlements aim to cultivate sufficient land to produce enough grain for consumption and sowing seed for the following year. Settlements can also cultivate a buffer of grain to protect against poor harvests. Settlements undertaking extensification use surplus grain to sow extra land. Settlements undertaking intensification cultivate the same area of land that they would under subsistence-based arable farming but by incorporating manure into the land settlements can boost annual grain yields and avoid the need to leave arable land fallow after use. Settlements are limited however by the availability of land, labour and sowing seed when undertaking arable farming, and in the case of intensification, manure.

The first experiment analysed the land and labour costs for subsistence-based arable farming undertaken by settlements of different sizes to better understand arable farming prior to Roman occupation in the Dutch *limes* zone before a shift to surplus production may have occurred. The focus was to identify the key limiting factors in subsistence-based arable farming as modelled and gauge their relative importance. The second experiment compared surplus grain produced under the three different surplus production strategies with their land and labour costs to provide a cost-benefit analysis. The cost-effectiveness of strategies was used to generate theories about optimum farming strategies. In addition, the relative limiting impact of the availability of land, labour (and manure) were gauged for the production strategies individually. The third experiment analysed subsistence and surplus arable strategies within reconstructed landscapes of the Dutch *limes* region based on paleogeographic data. This was used to analyse more realistic limitations on land availability as well as possible scenarios of land competition for different tasks.

An important element of arable farming considered only simplistically in this sub-model is the role of soil nutrients. The examples provided above include soil nutrient cycles within their arable sub-models to observe, for example, the impact of continuous cultivation (see Baum *et al.* 2016; Danielisová & Štekerová 2015). Although in ROMFARMS, yield increases through manure incorporation are included as well as the implications of fallowing, these are done simply and do not take into account the complex cycle of nutrients that have demonstrable effects on yield (see Baum *et al.* 2016). In addition, the landscape was modelled simplistically, only considering levees and flood-basins as suitable land for agricultural tasks as discrete landscape units (cf. de Kleijn *et al.* 2018).

8.2.2.3. Animal husbandry

A system dynamics model of herd dynamics was developed for the major livestock species that have been found in zooarchaeological assemblages of the region: sheep, cattle and horse. Settlements can be provisioned with a herd of each animal, with the size of the herd and the products they can supply (meat and milk from cattle and sheep, manure from cattle, wool from sheep and surplus immature animals from horses) emerging as a result of natural mortality rates, birth rates of adult female animals and slaughter rates. Slaughter rates vary depending on the management strategy undertaken by settlements in which they seek to maximise the output of a particular product which does not result in the extinction of the herd. These slaughter rates were developed from a previous study of animal husbandry by Joyce & Verhagen (2016).

The first experiment of animal husbandry was carried out to explore the yield outputs, herd size and composition, and land and labour costs for each of the animal husbandry strategies available to settlements. The calories available from meat and milk from cattle and sheep herds were compared with demand from settlements and the supply of calories from arable farming to analyse the proportion of the diet of inhabitants that could be animal-based. As with arable farming, exploring the role of land and labour as limiting factors was central to the discussion. Settlements require pasture and meadow land to keep animals and labour to collect fodder for

winter. The second experiment concerned the possibility of surplus production of animals. Labour availability was compared with labour costs for single and multiple herds of sheep and cattle to analyse the feasibility of surplus milk, meat or wool production. Important for the Dutch *limes* region, the third experiment analysed the land and labour costs for surplus production of horses. Animal husbandry was also simulated in reconstructed landscapes too to gauge the likelihood of land limiting surplus production of animal products.

The simulation of different animal husbandry strategies has so far not been implemented in agent-based models of agriculture in the past. Although the keeping of livestock is incorporated, neither Saqalli *et al.* (2014) or models developed by 'Social Modelling as a Tool for Understanding the Structure of Celtic Society and Cultural Changes at the End of the La Tène Period' project consider the implications of exploitation of animals for different products they supplied. Slaughter rates in these models reflect a trade-off between preventing the extinction of the herd and producing sufficient food for consumption (see e.g. Danielisová & Štekerová 2015), rather than a preference for a particular product.

8.2.2.4. Fuel and timber collection

An agent-based sub-model of wood collection was developed using a combined patch choice and central place foraging model for fuel and timber collection (after Shaw 2008). Settlements collect wood from the landscape, a resource spread heterogeneously throughout the landscape. The central behavioural rule determined the place where settlements collect fuel. The optimum area of the landscape for collection is the nearest cell or patch containing more wood than the average per hectare. If the amount of wood in the area chosen drops below this average the next nearest area with more wood than the average per hectare is chosen. This avoided using proximity as the sole criterion (see Shackleton & Prins 1992; also Shaw 2008; see Brouwer *et al.* 1997 for ethnographic evidence of wood collection). Woodland regrows in ROMFARMS unless the land is used for another purpose (e.g. arable farming).

Experimenting with wood collection focused on the developing theories about optimum strategies. Different scenarios were simulated in which inhabitants of settlements consumed wood at different rates and settlements collected wood at different frequencies. Deficits of wood experienced by settlements were compared to identify which scenarios were not feasible with the workforce available to settlements. Labour costs for wood collection were combined with the costs for other agricultural tasks to identify where possible labour shortages may have occurred throughout the agricultural year. In addition, the total consumption of wood under optimum strategies were calculated to develop theories concerning the necessary quantity of wood needed in the landscape and when strategies such as when woodland management strategies may have been necessary.

Saqalli *et al.* (2014) noted the importance of implementing fuel collection as a task to be included in implementations of their conceptual model, and it has been considered in previous agent-based models of the agricultural economy (see e.g., Baum *et al.* 2016; Danielisová & Štekerová). The focus in earlier models was on supply and demand, rather than methods of collection. The implementation of an agent-based sub-model utilising foraging theory has so far not been incorporated nor has the simulation of different scenarios of fuel collection strategies.

8.3. Principal findings and contribution to knowledge

The principal findings of this research can be divided into three key areas: the subsistence economy, surplus agricultural production and agriculture in the landscapes of the Lower Rhine delta. In the analysis of the subsistence-based agricultural economy characteristic of the study region in the Late Iron Age, focus was placed on developing more detailed knowledge of land and

labour costs for subsistence-based arable farming, animal husbandry, and fuel and timber collection. Similar results were sought for different strategies of surplus production in animal husbandry and arable farming to analyse the possible limiting impact of different factors on agricultural production shifted from subsistence-based production in the Roman periods. Whilst these areas of investigation used randomly-generated landscapes, further experiments used reconstructed landscapes to gauge the impact of the natural landscape of the Lower Rhine delta on both subsistence- and surplus-based farming.

8.3.1. Subsistence farming in the pre-Roman Late Iron Age

Modelling results from experiments with subsistence-based arable farming identified the availability of land, labour and sowing-seed as limiting factors in the settlements' ability to cultivate sufficient land to produce grain to be consumed by inhabitants, sowing seed for the following year and a small surplus, or buffer, to protect against negative fluctuations in grain yield. Settlements that do not produce at least 50% more grain than needed for consumption and sowing seed will, when yield falls below the average predicted by settlements, have a deficit of sowing seed for the following year as grain that is needed for sowing seed is consumed by inhabitants to fulfil their immediate needs. The necessity of a buffer for subsistence-based farmers has been noted previously (see e.g. Groot & Lentjes 2013; Halstead & O'Shea 2004) and the modelling results are in line with their assumptions and observations. With the mean workforce available to settlements, settlements are restricted neither by the availability of labour nor by the availability of land in randomly-generated landscapes.

Simulations of different animal husbandry strategies produced new results regarding possible outputs from modelled herds. The relative difference in the quantity of products supplied by simulated cattle herds generally corresponded with the exploitation strategy: cattle exploited for meat had the highest output of meat; cattle exploited for milk had the highest output of milk. Owing to the smaller herd size of cattle exploited for manure that emerged in the simulation, the output of manure is lower than cattle exploited for milk or meat. In contrast, experiments with different exploitation strategies of sheep showed that both the size and the yield of products does not differ greatly among the different strategies. The results enabled theories regarding the relative importance of cattle and sheep within the diet and economy. The relatively small yields of meat and milk from modelled sheep herds compared with yields from cattle indicates that sheep may have been of minor importance in the diet of inhabitants. The higher yields of meat and milk from simulated cattle herds, especially those exploited for meat or milk, points to a greater importance in the diet of subsistence-based farmers of cattle meat or milk. Settlements with three or five households would still need to keep more animals than contained in one simulated herd to have access to enough meat and milk to make up the shortfall of calories not derived from grain assuming a 67.5:22.5:10 ratio of grain, animal products and other food sources in the diet of the inhabitants. However, sufficient labour is available for larger settlements to be able to collect fodder for more animals.

By experimenting with different firewood collecting behaviours, theories regarding their optimum strategies were generated. As settlements consume more wood per capita per day, the frequency that settlements can collect firewood reduces. Accordingly, a consumption of 5kg per capita per day requires daily collection of firewood by settlements before large deficits occur. Furthermore, the simulation results show that c. 7kg is the maximum per capita daily consumption rate. Settlements consuming more than this amount would experience large deficits of firewood even if daily collections are undertaken.

Experiments of the rural economy assumed for the pre-Roman Late Iron Age in the Dutch *limes* zone have produced results for the land and labour costs for subsistence-based farming. By

simulating the agricultural tasks in unison, periods during the agricultural year where so-called labour bottlenecks could have occurred have been identified. These are periods where the workforce available to settlements is insufficient to complete tasks within the allotted period of the year. In those scenarios where settlements have an average-sized workforce, all tasks can be completed within the allotted period by the “strong” workforce (adult men and women) and the “weak” workforce (adolescents and the elderly) with the latter only able to help undertake firewood collection in ROMFARMS. However, the number of adults inhabiting a settlement with single households can, in a minority of scenarios, decrease to one individual which is insufficient to allow settlements to collect animal fodder and collect enough fuel. For settlements with more households, the likelihood of the number of adults falling below what is necessary to complete agricultural tasks in the allotted time is small.

8.3.2. Surplus production in the Dutch *limes* zone

Settlements in ROMFARMS can produce surplus grain under all three arable strategies simulated: subsistence-based arable farming, intensification and extensification. Surplus was considered to be any grain that exceeded the grain needed by the agrarian settlement for consumption, sowing seed and a buffer. Under subsistence-based farming, surplus production of grain is not the behavioural goal of the arable strategy undertaken but rather a consequence of settlements cultivating a buffer and coping with annual fluctuations in yield. Therefore, when yields fluctuate above the mean yield, a small surplus is produced by settlements. However, yields are produced sporadically and depend on a random factor. Furthermore, the quantity of surplus produced is minimal. If the production of a surplus of grain is desired by settlements, a shift from subsistence-based to some form of surplus arable production is necessary.

In contrast to previous models of the ancient agricultural economy in the Dutch *limes* zone, ROMFARMS was created as a tool to explore the effects of different agricultural decisions. Thus, different ways that settlements in the study region during the Roman Period could have produced surpluses of grain were investigated by exploring the effects of different parameter values that simulate different agricultural behaviours. In arable farming, strategies of arable intensification and extensification were analysed and compared in terms of relative differences in the quantities of surplus grain produced and land and labour costs. In addition, the relative impact of various limiting factors was gauged and compared for the two strategies of surplus arable production. The results showed that settlements in randomly-generated landscapes will produce more surplus grain when undertaking arable extensification than when undertaking arable intensification. The results showed also that settlements of different sizes will continue to produce different quantities of surplus grain, with larger settlements producing greater quantities of surplus grain than smaller settlements. For settlements undertaking arable intensification, this difference was owing to the different sized areas of land that settlements will cultivate. Whilst no extra land is cultivated by settlements undertaking arable intensification, larger settlements will still cultivate larger areas of land than smaller settlements. Under subsistence-based arable farming and arable intensification the area of land cultivated remains a direct function of the number of inhabitants and the quantity of grain required per inhabitant. Larger settlements will produce greater quantities of surplus grain when undertaking arable extensification because the larger workforce available to larger settlements can cultivate greater areas of arable land. The results also showed differences in land costs and labour costs between the two strategies of surplus arable production. Most of these differences were owing to in-built rules and assumptions used in ROMFARMS. Behavioural rules determine that land use will be less when settlements undertake intensification than when settlements undertake extensification. Furthermore, assumptions used for time taken to complete arable tasks, ploughing, sowing, harvesting and applying manure, cause different estimations of labour costs for the two

strategies. Most differences between the two strategies were therefore not emergent phenomena of the simulation. The results did show, however, that consumption requirements of a settlement's inhabitants had less impact on land-use patterns when settlements undertake extensification. In these scenarios, settlements will cultivate the largest area of land possible under the constraints of the availability of land, labour and sowing seed. Surplus grain produced when settlements undertake arable intensification or subsistence-based arable farming is connected to consumption patterns. The more grain that the inhabitants of farming settlements need when undertaking these strategies, the greater the area of land to be cultivated. This increases the potential quantity of surplus grain. Land-use did not change when the proportion of the diet that was grain-based increased or decreased when settlements undertook arable extensification. An assessment of cost effectiveness in terms of land and labour use for both surplus arable farming strategies indicated possible differences in their optimal usage. Per unit of surplus grain, settlements undertaking arable intensification will use a smaller area of land than settlements undertaking arable extensification. Conversely, labour costs per unit of surplus grain produced are smaller when settlements undertake arable extensification. These results indicated that when settlements had reduced access to arable land, a strategy of intensification was a more advantageous response to the need to produce surplus grain. When labour availability was more limiting, a strategy of arable extensification was more efficient.

In randomly-generated landscapes, the relative impact of limiting factors was gauged for both arable intensification and extensification. For the former strategy, the results showed that the availability of labour was not limiting. Despite having to undertake an extra, labour-intensive task of applying manure to arable land in an already labour-intensive period of the agricultural calendar, the areas of land settlements cultivated were small enough that sufficient labour was available to undertake the task in the allotted period. Settlements undertaking intensification in randomly generated landscapes were most limited by the availability of manure and thus, by extension, the availability to manage cattle. Without manure, the quantity of surplus grain settlements could produce would be small as it is when settlements undertake subsistence-based arable farming. Settlements undertaking arable extensification in randomly-generated landscapes are mostly limited by labour. The land available to settlements each year was greater than the labour pool available to each settlement could cultivate. In particular, the area of land was greater than could be harvested by each settlement within the strict fourteen-day period that ROMFARMS allotted as a harvest period.

Although not implemented in ROMFARMS currently, the possibility for settlements to undertake both intensification and extensification concurrently was discussed briefly with regards to the impact of different limiting factors. To do so would require both an increased availability of arable land than would be needed under intensification alone and therefore an increased availability of manure. For the latter, settlements would need to keep more animals than they are provisioned with in ROMFARMS. Herds of at two to three times the size as those simulated in ROMFARMS would be needed per settlement to produce sufficient manure to apply the increased area of arable land cultivated for the optimum application rate of 10t/ha. The results showed that, as far as the availability of labour limited settlements in arable farming and animal husbandry, a combined strategy of arable intensification and extensification was feasible.

The possibilities for surplus production of animal products as a mechanism for native, agrarian settlements to supply consumer settlements in the Dutch *limes* zone was also analysed. As with the analysis of the surplus production of grain, the impact on land and labour use was assessed for surplus-based animal husbandry to identify where the availabilities of these two resources could have limited rural settlements. A small surplus of animal products could be produced by settlements undertaking subsistence-based animal husbandry whereby the primary

behavioural goal of settlements is to produce enough meat and milk for the needs of inhabitants only. The larger the settlement, the smaller the available surplus as more meat and milk is consumed in larger settlements owing to the larger number of inhabitants. This was not an emergent quality of the simulation, however, and was owing to how subsistence-based animal husbandry is simulated in ROMFARMS. The simulated herd is the basic unit of animal husbandry in ROMFARMS. Accordingly, settlements are provided not with absolute numbers of animals but with herds which all have a standard starting size of thirty animals with the herd size emerging stable with different sizes. Settlements, regardless of size, are provided with one herd upon creation in the simulation and therefore the same number of animals which necessarily results in a larger excess of animals for small settlements. It was noted that this was not a realistic representation of animal husbandry in the past but is one of the many possible management strategies available.

Alternatively, the feasibility of an extensive animal husbandry strategy was considered in relation to the availability of labour for settlements of different sizes. The results showed that with the labour available to settlements of all sizes, settlements can collect sufficient fodder for more animals than in a modelled herd simulated by ROMFARMS. An extensive surplus animal husbandry strategy is therefore not made infeasible by the availability of labour. The results also showed that the quantity of surplus meat and milk available from sheep herds were very small. Although settlements are not restricted by labour availability to keeping one modelled herd's equivalent number of sheep, the number of animals required before surpluses are available is very large which is not reflected in the archaeological record. In particular, the relative proportion of species in zooarchaeological assemblages indicates the importance of cattle over sheep. The results suggested that meat and milk from sheep herds had a more limited role in the production of surplus food in the study region compared with cattle. It is probable that wool, as a unique product provided by animals kept in the study region, was economically more important with sheep husbandry becoming a specialised response. The exploitation of sheep for wool may not be reflected in reconstructed management strategies of the past however as the results show that the quantity of wool supplied by different types of sheep herd does not change significantly.

Remains of horse in zooarchaeological assemblages of rural agrarian settlements in the Dutch *limes* zone are almost ubiquitous and it has been argued that horse played an important part in the economy of the region with horses becoming surplus commodities. Simulations of horse herds where the primary aim is to maximise the number of immature animals that can be removed from the herd without causing the extinction of the herd showed that a surplus of seven animals was available from the simulated herd. Not all settlements in the Dutch *limes* zone would be required to undertake surplus production of horses to produce sufficient equids each year for the Roman army. Given the frequency of horse bones in assemblages and variations in the relative abundance compared with other livestock, it was concluded that not all settlements would have managed horse herds of c. 51 animals as simulated in ROMFARMS. The simulated horse herds in ROMFARMS are indicative of specialised breeding, with other settlements undertaking *ad hoc* or small-scale horse breeding which required different strategies that ROMFARMS currently does not simulate.

8.3.3. Agriculture in reconstructed landscapes

By taking advantage of the GIS extension of NetLogo different agricultural strategies were simulated both in randomly-generated landscapes and reconstructed landscapes from paleogeography data produced by Groenhuijzen (2018). The total area of the study region with evidence of habitation from the Late Iron Age to the Middle Roman Period A was divided into equal sized 32 sub-regions with an area of 100km². Rasters of the palaeogeographic

reconstructions were imported for each sub-region. The different agricultural strategies with the limitations and opportunities of the natural landscape in the Lower Rhine delta applied. Settlement densities calculated from a data-set of rural settlement sites present in each sub-region were used to determine the maximum number of settlements that could emerge from the simulation and ranged from 0.01 to 0.81 settlements per km² (cf. van Dinter *et al.* 2014 and De Kleijn *et al.* 2018 who use estimated absolute numbers of settlements). The actual location of settlements was not simulated.

A principal aim of simulating agriculture in environments using reconstructed palaeogeography and settlement densities was to investigate how the availability of land in each sub-region could have limited settlements undertaking different agricultural strategies. In scenarios that simulate agriculture in randomly-generated landscapes, the availability of land was not limiting owing to the environmental conditions settlements were placed in. The areas of arable land and pastoral land were unrealistic and not representative of any actual landscapes in the past. Accordingly, the limiting impact of land availability could not be gauged for the Lower Rhine delta in the past. Results from simulating agriculture in landscapes generated from paleogeography reconstructions showed that the availability of land limits agricultural productivity differently under different strategies. When settlements undertook either subsistence-based arable farming or arable intensification, the availability of land was not limiting in any scenario. Total land usage, even in scenarios where landscapes were occupied by large settlements with five households, remained lower than the maximum available area. In scenarios where settlements undertook arable extensification, the total land used in each sub-region increased owing to differences in land use per settlement under this arable farming strategy. In a majority of sub-regions, the total area used remained lower than the maximum area of arable land available, however. Only in those sub-regions where the total available arable land was very small and the size of settlement occupying the landscape was large (five households), could the availability of land be identified as more limiting than the availability of labour. Landscapes occupied homogeneously by settlements with five households were considered unrealistic of any landscape in the Lower Rhine delta, however, indicating that for arable farming in the study region during the Late Iron Age and Roman period, the availability of land would not have been the principal limiting factor.

Comparisons of the area of pasture and meadow land required by cattle herds exploited for different products and the area of suitable land available in each sub-region generated different results regarding the limitations that land availability placed on animal husbandry in each sub-region. In scenarios where agrarian settlements kept cattle to produce meat and milk for the needs of the inhabitants and, when settlements undertake arable intensification, to produce manure, the number of animals needed were relatively low. The equivalent number of animals in one to two simulated herds, depending on the size of settlement, produced sufficient meat, milk and manure. The area of pasture and meadow land required when settlements undertake subsistence-based animal husbandry or animal husbandry to complement arable intensification was low.

Land costs for an extensive animal husbandry strategy were calculated and compared with available land to produce indications of where in the study-region the availability of land could have been more limiting than the availability of labour. It was assumed that the behavioural goal of settlements undertaking an extensive animal husbandry strategy is to keep as many animals as the availability of land and labour permits. Differences in the availability of land and settlement density among sub-regions caused different results when gauging the relative limiting impact of land and labour availability. In landscapes occupied homogeneously by settlements with one household, the availability of labour was more limiting in all but a few sub-regions in both the

Early and Middle Roman Periods In scenarios with larger settlements, the results were more mixed. In the central and eastern parts of the Lower Rhine delta, the availability of land was high enough so that labour was not as limiting as the availability of labour. In other sub-regions, the availability of land was more limiting. In scenarios with settlements of the largest simulated size, the available labour would allow settlements to manage more animals than could be supported by available land in almost all sub-regions in both periods except when estimated settlement density was very low.

In addition to assessing the relative impact of land availability on the ability for settlements in the past to undertake both subsistence-based and surplus strategies of arable and pastoral farming, an assessment of possible instances of land competition among agricultural tasks was made. The results indicated few instances where the use of land for one agricultural task would reduce the availability of land to an extent that would restrict the ability for settlements to undertake another agricultural task. In scenarios with small settlements with one or two households, the total area of land used by all settlements in the simulation for both extensive arable farming and extensive arable husbandry is small as a result of labour restrictions. The results indicate that both surplus production strategies could have been undertaken simultaneously in sub-regions occupied homogeneously by small settlements. The results from simulating agriculture in sub-regions occupied by larger settlements were different. In some areas of the Lower Rhine delta, by undertaking arable farming in any form, settlements restrict the maximum number of animals that can be managed with available land resources. In landscapes with settlements with three households, the use of potential arable land as pasture or meadow land can result in the availability of labour becoming more limiting. In sub-regions occupied by settlements with five households, although the maximum number of animals that can be kept increases when settlements use potential arable land, the availability of land remains more limiting than the availability of labour.

8.3.4. Reconstructing supply and demand in the sub-regions

Despite the difficulties in estimating demand for food in the Dutch Roman *limes* zone by soldiers and the inhabitants of towns and *vici*, an assessment of the extent to which local settlements could supply consumers in the region was provided. It was noted that an inventory of forts, *castella*, *vici* and towns was extremely difficult to produce. Issues relating to identifying the existence of sites, ascertaining their function and determining their chronology were discussed which has resulted in a list of certain and uncertain sites. Estimates of populations of these settlements at any point in their occupation is even more uncertain. Estimating possible supply in the region was equally uncertain. The inventory of rural agrarian settlements in the data-set used is unlikely to be representative of the actual historical situation at any point in the Roman period. Furthermore, determining the start and end date of occupation for rural settlements is inexact. The calculated demand and supply in each of the thirty-two sub-regions reconstructed for this study are likely to be under- or over-estimations depending on the sub-region and period.

The model was useful in establishing bandwidths of supply and demand which enabled an assessment of the feasibility of differently scaled supply networks was provided. Demand for grain for human consumption or grain for use as fodder was estimate for each sub-region and each period. In addition, the quantity of meat and milk required was also calculated. Owing to uncertainties related to the size of rural settlements in the Late Iron Age and Roman period, scenarios were simulated in which reconstructed landscapes were occupied by settlements of different sizes. These scenarios assumed a homogeneous occupation by settlements with the same number of households. In addition, to observe changes over time, scenarios were simulated using different settlement densities calculated for each sub-region in each of the time periods

used in the study: the Late Iron Age (250 BCE to 12 CE), the Early Roman Periods A & B (12 BCE to 70 CE), and the Middle Roman Periods A & B (70 CE to 270 CE).

Two mechanisms of supply were envisaged: a micro-regional supply network whereby settlements located in the environs of forts, *castella*, *vici* or towns supplied them directly; and, a macro-regional supply network in which the sum total of grain and animal products from all settlements within the Dutch *limes* region was used to supply each of the consumer settlements. A supra-regional supply network whereby consumer settlements located in the study region were food produced by both settlements within and without the Lower Rhine delta fell outside the possible remit of this research. A micro-regional supply network was deemed feasible in a sub-region when the total quantity of grain or animal products produced by rural settlements located in the sub-region was equal to or exceeded the total quantity demanded by any consumer settlements present. A macro-regional supply network was deemed feasible if the sum total of grain or animal products produced by all settlements located in the study region equalled or exceeded the total demand from all consumer settlements present in each period.

In the Late Iron Age, demand from grain potentially came only from the early legionary camp located in Nijmegen. Settlements during this period are assumed to have undertaken subsistence-based agriculture, with any surpluses unguaranteed and produced because of the positive impact of exogenous forces, such as climate. Settlements occupying the same sub-region as the legionary camp at Nijmegen would have produced much less surplus grain than required by the soldiers present rendering a micro-regional supply network infeasible. Similarly, a macro-regional network was ruled out based on possible quantities of grain that could have been produced by all settlements in the region concurrent with Nijmegen-Hunerberg practising subsistence-based farming. If grain was consumed by animals attached to the army based at Nijmegen, a micro-regional supply network remains infeasible. A macro-regional supply network of animal products was also feasible in more scenarios than for grain for human consumption. Provided soldiers also consumed dairy products, the sum total of meat and dairy products produced in the entire study region was sufficient to have supplied the soldiers located in Nijmegen. Macro-regional supply however relies on the relatively rapid development of a sophisticated supply network that is not probable. In addition, it is probable that this settlement was occupied only temporarily which makes such a supply network unlikely. Furthermore, faunal remains from this settlement indicate the predominance of pig in the soldiers' diet rather than locally produced cattle (Cavallo *et al.* 2008). Archaeobotanical remains are not numerous and inconclusive relating to local supply of plant products however (*ibid.*). The results indicated that local supply by rural settlements to the legionary camp at Nijmegen was possible for some products (grain for horses and animal products), however, archaeological evidence suggests that it was not probable.

In the Early Roman period, several more permanent military settlements develop increasing the year-round demand of grain and animal products. In the Early Roman Period A, only three military settlements were occupied. The number of military settlements increases substantially in the Early Roman Period B, with many of these settlements occupied throughout the following Middle Roman Periods A and B. In the Middle Roman Period, the region also saw the development of towns and *vici* inhabited by non-agrarian civilians who could have also been supplied by native rural agrarian settlements. Archaeological evidence from producer and consumer-only settlements from the Early Roman Period onwards points to increasing integration of rural settlements into the macro-economy of the Lower Rhine delta as well changes in agricultural strategy from subsistence farming to small-scale surplus production. The scenarios simulated for these periods assumes that settlements undertook some form of surplus production: arable intensification or extensification, or extensive animal husbandry.

The results from numerous scenarios simulated produced some trends regarding supply and demand in the Roman period when native agrarian settlements were involved in the supply of grain and animal products to military settlements, towns and *vici*. Supply in each sub-region is determined by the reconstructed settlement density, the size of the simulated settlements and the agricultural strategy employed. The results show that supply of grain is highest in sub-regions occupied by settlements with five households, sub-regions with a relatively high settlement density and when settlements undertake arable extensification rather than arable intensification. A micro-regional supply network was assessed to be infeasible in many scenarios both when settlements undertook extensification or intensification. When sub-regions were occupied by settlements with one household, the total amount of surplus grain produced could fulfil only a small proportion of the total amount of grain demanded in sub-regions occupied by consumer-only settlements. Whilst the proportion increased somewhat in scenarios where settlements undertook extensification and over time, as settlement density increased from the Early Roman period to the Middle Roman period, a micro-regional scale was largely infeasible. However, as the size of the settlement simulated increased in scenarios, the proportion of grain that could be supplied by local agrarian settlements also increased. A micro-regional scale of supply became more feasible as the size of the settlement simulated increased, therefore. Although a homogeneous occupation of each sub-region is an unrealistic representation of settlement occupation in the past, the limited archaeological evidence available indicates that large settlements with three or five households were not common throughout the whole region (van Dinter *et al.* 2014, 39). There were of course regional differences. Vos (2009), for example, identified larger settlements with at least three to four farmsteads (or households in ROMFARMS) per settlement. The results indicate that a micro-regional supply network of grain to military settlements, towns and *vici* for human consumption was infeasible based on what has been assumed about rural settlement sizes in the Roman period in the Lower Rhine delta. A micro-regional supply network could not be rejected outright however as at least a very small proportion of the total grain demanded can be produced by local agrarian settlements in scenarios with settlements with one or two households.

The results from comparisons of total supply and demand of grain for human consumption in the whole Lower Rhine region in the Early and Middle Roman periods show that a macro-regional supply network was feasible in more scenarios. Including scenarios where settlements possess one household, a majority proportion of grain demanded by military or civilian settlements can be fulfilled by the sum total of surplus grain produced in all sub-regions. Whilst a micro-regional supply network in scenarios where settlements undertook arable intensification was ruled out on the basis of surplus grain produced per sub-region, a macro-regional supply network would have been feasible although the total proportion of grain demanded that could have been fulfilled by local supply was smaller. As settlement densities increased in each sub-region from the Early Roman period to the Middle Roman period, so too did the estimated quantity of surplus grain produced, increasing the total quantity of grain that could have been supplied to settlements not producing their own.

The calculations for demand and supply of grain for human consumption assumed the use of grain as a staple foodstuff. They do not consider use of grain for other products. Notably not included are estimations of the demand for barley in particular to produce beer. Although beer was not a standard ration provided to soldiers (cf. *Tab. Vindol.* III 628; Nelson 2005, 65), it was almost certainly consumed by them particularly in the northern provinces. There is evidence to point to substantial beer production in Britannia, Northern Gaul and Germania throughout Roman rule (Nelson 2005). As a commodity it is probable that beer was also consumed in the *vici* and towns. Estimates of the quantity of grain required for beer demand were not available. The quantity of barley that can be supplied would not differ from the results already gained from

simulations. A macro-regional supply network would remain more feasible than a micro-regional supply mechanism therefore if the quantity of grain demanded for brewing was as large as that needed for production of food for humans.

Botanical assemblages from native agrarian settlements have shown that mostly barley and emmer wheat were cultivated locally rather than bread and spelt wheat which is traditionally considered the staple grain of the Roman army. As a result, the likelihood of human consumption of barley and emmer wheat in forts, towns and *vici* has been questioned. A comparison of supply and demand for grain for use as animal fodder was also calculated using estimates of the number of cavalry in the Lower Rhine delta. The estimated population of horses was however very uncertain and did not include the many horses and equids that were used as pack animals and for other non-military purposes. A preliminary assessment of the feasibility of micro-regional and macro-regional supply was still possible despite the uncertainty of equid population estimates. Micro-regional supply of animal fodder from the Early Roman period to the Middle Roman period is infeasible in many scenarios. In landscapes occupied by small settlements comprising one or two households, only a small proportion of the total fodder required can be fulfilled by local surplus production. Whilst larger settlements can produce more grain fodder, landscapes occupied homogeneously by large settlements are unrealistic. Increases in the equid population from the Early Roman period to the Middle Roman period further reduces the proportion of the total grain demanded that can be fulfilled by local production. A micro-regional supply network is made more unlikely given the underestimation of the number of animals requiring fodder. When the sum total of surplus grain is compared with total demand, the results show that a macro-regional supply network of grain fodder is more feasible, including when landscapes are occupied by small settlements with one or two households and when settlements practice arable intensification.

Surplus production of animal products was also considered a strategy for local agrarian settlements to supply forts, towns and *vici* throughout the Roman period. Supply and demand for meat and milk supplied by cattle were compared. Meat and milk from sheep were not considered in calculations because the results of simulating sheep herds in randomly-generated landscape showed that animal products available from them were minimal. The calories available from meat and milk produced in sub-regions were estimated both when settlements undertake animal husbandry as ancillary to arable intensification, and when settlements undertake extensive animal husbandry. When settlements practice animal husbandry as auxiliary to arable intensification by exploiting cattle for the production of manure and to use as traction animals, the number of cattle kept by settlements is relatively small. As a result of the exploitation strategy and the low numbers of animals managed by settlements, the surplus milk and meat produced by settlements is not significant. The proportion of demand that can be fulfilled by agrarian settlements on a macro-regional scale is small and smaller still when a micro-regional supply network is used.

The surplus meat and milk available from settlements undertaking extensification of animal husbandry has been calculated on the basis of settlements keeping as many cattle as the availability of land and labour permitted. Although unrealistic, these calculations show the potential maximum meat and milk production in the sub-regions as limited by land and labour. The results showed that the surplus milk and meat produced by settlements undertaking extensification of animal husbandry is significantly greater. A micro-regional scale was shown to be feasible in most scenarios, except when demand was very high. A macro-regional supply scale was shown to be feasible in all but one scenario. The results indicated again that a macro-regional supply network was a more feasible mechanism for the surplus production of food. In addition, the availability of land and labour may not have restricted the ability of settlements to produce

surplus meat and milk. Whilst the availability of resources may not have restricted surplus production of animal products, the archaeological evidence from the region does not corroborate the practice of extensification of animal husbandry. Van Dinter *et al.* (2014) argued that there was no evidence for increases in stable sizes within byre houses in rural settlements nor evidence for the size of herds calculated in ROMFARMS. Surplus production of animal products was therefore not limited by any factors simulated in ROMFARMS.

8.3.5. Evaluation of method

8.3.5.1. Limitations of methods

Several limitations were identified during the implementation of ROMFARMS and the simulation of scenarios. Firstly, the availability of data to produce assumptions was not consistent. In the case of some aspects of the agricultural economy, no data from either regional specific or analogous research was available. When data was available, it was rarely available directly from archaeological sources from the Dutch Roman *limes* zone. Data from archaeological, ethnographic or experimental studies was not available to provide assumptions of the time taken to undertake agricultural tasks such as manuring, processing of timber or the production of hay fodder for example. Certain assumptions were therefore generated from reasonable estimates. For other assumptions, previous research indicated a lack of agreement with the assumptions used for ROMFARMS taken from the mean of available assumptions. The implications on the results produced by ROMFARMS are that quantities of agricultural production or labour costs for different strategies are tentative. However, ROMFARMS makes use of the best available domain knowledge for its assumptions. When more domain knowledge becomes available, the model can only improve as its assumptions can be updated and amended. It is hoped also that as more data becomes available the relative differences between strategies will not differ significantly. Conclusions have been made based on simulation results, but it is not assumed that the results represent actual yields of land and labour expenditure in the past. However, by simulating using a range of possible assumptions, the bandwidth of outputs will include a result that is representative of the situation in the past.

In the implementation of ROMFARMS, a trade-off between simplicity and detail was necessary. Animal husbandry strategies simulated include only basic exploitation strategies where kill-off patterns maximise the return of a single product. The results from calculations of micro- and macro-regional supply depend on the yields from different herds of animals as simulated in ROMFARMS which are just some of the possible ways that farmers in the past could manage animals. Similarly, different strategies of arable farming concern only the investment of land and labour. Other strategies, such as multiple croppings each year or mixed cropping are not considered. Some of the processes simulated in ROMFARMS have also been simplified for the purposes of simulation. Comparisons between ROMFARMS and other simulations of the agricultural economy in the past have already been provided. The sub-model of population dynamics is significantly less complex than that produced by Verhagen *et al.* (2016a) or Danielisová & Štekerová (2015) for example. The simplification of this sub-process has an impact on the results generated by ROMFARMS as rural demand of resources and labour supply are dependent on populations in the landscape. A further comparison can be made regarding the lack of a soil nutrient cycle used in ROMFARMS (c.f. Baum *et al.* 2016; Danielisová & Štekerová 2015). The impact of manuring or fallowing on soil productivity are considered only superficially despite the potential impact that soil nutrients could have had on arable yields in the past.

Further simplifications include the restricted inclusion of adaption of agriculturalists in ROMFARMS. The impact and adoption of mitigating strategies when settlements experience fuel or grain deficits have not been included. Neither have the impact or adoption of strategies when

settlements experience labour shortages. ROMFARMS was also implemented based on a discrete patch model wherein cells have only one landscape element or use. This may have caused the overestimation of certain resources such as grassland, arable land or woodland. In addition, defining landscape suitability as suitable or not suitable for different parts of the agricultural economy is more simplistic approach than that undertaken by de Kleijn *et al.* (2016, 2018). Simplification of landscapes simulated by ROMFARMS also concerns scenarios with homogeneous occupation by settlements of the same sizes. Such landscapes are not realistic, but it was chosen to simulate landscapes in this way to produce a range of possible results from minimum to maximum population sizes.

ROMFARMS was developed based on settlements behaving in an economically rational way. There is little inclusion of socio-cultural factors which were difficult to translate into behavioural rules. Roman macro-economic policies have not been included therefore and the impact of activities from military settlements, towns and *vici* have not been considered. The way that surplus food was demanded in the past is also only briefly considered despite its potential impact on how local farmers responded to the demands of consumers in the region. Taxation, trade in kind, monetary trade or forced acquisition are some of the ways surplus food could have been demanded and they would have had different impacts on responses from farmers. Local cultural factors have also been excluded from ROMFARMS. Some of these factors could include local exchange networks, familial networks, social and settlement hierarchies, communal labour and land ownership. Farmers in ROMFARMS are of the species “*homo economicus*” which, whilst expedient, simulates only one aspect of their behavioural goals. Farmers in the past had both economically rational behavioural goals and behavioural goals shaped by the socio-political sphere.

The choice of software also presented limitations. There is an upper limit of the number of agents that could be simulated by NetLogo and as a result, the whole region was divided into thirty-two sub-regions. Owing to this, the effects and impact of limiting factors on agriculture in the whole macro-landscape could not be simulated. Macro-regional scenarios were therefore missing from the scenarios simulated by ROMFARMS. Different tasks in the agricultural calendar occur at different frequencies in ROMFARMS, requiring reconciling of different temporal scales. For example, fuel collection strategies occur multiple times throughout the year depending on the value of the parameter “*collection-frequency*”. In addition, collection and production of timber can occur multiple times in one step of the simulation as foragers require multiple trips to collect sufficient timber. The simulation of processes multiple times within each step, significantly increase processing time which restricted the number of scenarios that could be feasibly simulated.

ROMFARMS has successfully produced detailed results for the baseline economy of the Lower Rhine delta from the Late Iron Age to the end of the Dutch *limes*. The development of a null scenario i.e. an economically rational scenario, is the first step in the reconstruction of a palaeo-economy and provides the foundations for the development of further and more nuanced hypotheses regarding limitations and opportunities for agriculture in the region. ROMFARMS was specifically developed for this research and is a unique and innovative tool to achieve specific objectives. It is also a significant addition to the existing toolkit not only for Dutch Roman archaeology, but for the investigation of agriculture in the past in general. The parameter space of ROMFARMS is large and simplifications of scenarios was necessary. Complete exploration of all permutations of variable values was not possible, therefore. The number of scenarios simulated was nevertheless extensive. As a result, ROMFARMS has successfully been used to reject some scenarios as infeasible and accept others as possible within the confines of both the cultural and natural landscapes of the Lower Rhine delta in the Late Iron Age and Roman periods.

The spectrum of untested scenarios has been significantly reduced allowing for more focused exploration of the limits of agriculture in the *limes* zone. Understanding of the palaeo-economy of the Dutch *limes* zone has therefore benefitted from empirical analysis of results from the simulation of explicit scenarios of a formal and spatially dynamic agent-based model.

8.3.6. Opportunities

The results from simulating different agricultural strategies using ROMFARMS have generated new hypotheses about how surplus production of animal products and grain could have been undertaken by settlements in the Roman period in the Lower Rhine delta. In particular, it has produced new results concerning the relative limiting impact of different factors of production: land and labour. These new hypotheses and results, coupled with the development of a new tool, have meant that ROMFARMS is a significant contribution to the surplus debate in Dutch Roman archaeology. In addition, it joins the growing number of agent-based modelling approaches that have been used successfully to analyse different elements of the agricultural economy in the past. Nevertheless, further development and implementation of ROMFARMS has been envisaged. The development of the landscape sub-model in ROMFARMS could enable the incorporation of approaches that have been used successfully before (see e.g. de Kleijn *et al.* 2016; 2018). The development of patch choice and suitability models for arable farming and animal husbandry, the implementation of a continuous patch model and heterogeneous occupation of landscapes would allow for the simulation of landscapes in a more realistic manner.

Development of the simplified sub-model of settlement population dynamics in ROMFARMS should be a priority. The impact of recruitment for the Roman army has been the subject of debate in Dutch Roman archaeology (see e.g. Bloemers 1978; Willems 1986; Vossen 2003; Verhagen *et al.* 2016a). Its impact on the labour pool has also been considered (see e.g. van Dinter *et al.* 2014; van Driel-Murray 2008). By incorporating recruitment into the population sub-model, its effects on labour supply can be simulated and quantified. Furthermore, populations in ROMFARMS are stationary with insignificant annual growth. In contrast, the ‘Social Modelling as a Tool for Understanding the Structure of Celtic Society and Cultural Changes at the End of the La Tène Period’ project has used differing population profiles within simulations. Simulating agricultural strategies under the conditions of increasing and declining populations would enable further hypotheses to be generated related to the relative limiting impact of land and labour resources in the Dutch Roman *limes* zone. This can be achieved using different life-tables and the development of further “what-if” scenarios using artificial values for mortality rates.

Another priority for development is to depart from the economic rationalism of ROMFARMS and incorporate socio-political and cultural factors. The translation of such factors into behavioural rules that can be simulated is complex but has been attempted in previous research (see e.g. Danielisová *et al.* 2015). This would enable the inclusion of the significant body of archaeological research in the area that does not concern the economy of the region.

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Appendices

PARAMETER	RANGE	INCREMENT	DEFAULT	NOTES
NO-1-HOUSEHOLD-SETTLEMENTS	1-9999999999999999	1	2	<i>Actual maximum capped by area of levees and settlement density</i>
NO-2-HOUSEHOLD-SETTLEMENTS	1-9999999999999999	1	2	<i>Actual maximum capped by area of levees or settlement density</i>
NO-3-HOUSEHOLD-SETTLEMENTS	1-9999999999999999	1	2	<i>Actual maximum capped by area of levees and settlement density</i>
NO-5-HOUSEHOLD-SETTLEMENTS	1-9999999999999999	1	2	<i>Actual maximum capped by area of levees and settlement density</i>
RUNTIME	1-9999999999999999	1	100	<i>Number of steps in each simulation run</i>
REGION	"hyp", 1-32	-	-	-
PERIOD	IJZ, ROMVA, ROMVB, ROMMA,ROMMB	-	-	-
AREA-LEVEE	0-1	0.01	0.5	<i>Percentage of total patches assigned "levee" for landscape-type variable</i>
AREA-FLOODBASIN	0-1	0.01	0.5	<i>Percentage of total patches assigned "flood-basin" for landscape-type variable</i>
FOREST-COVER	0-1	0.01	0.1	<i>Percentage of total patches with woodland</i>
FEN-COVER	0-1	0.01	0	<i>Percentage of total patches that are neither assigned "levee" nor "flood-basin" in randomly-generated landscapes</i>
%-CALORIES-FROM-CROPS	0-1	0.01	0.7	<i>Percentage of total calories required by the inhabitants of settlements that are derived from grain</i>
STORE-SIZE	1-99	0.1	1.5	<i>Percentage of total grain required that is required as extra buffer</i>
STRATEGY-ARABLE	"none", "extensification", "intensification"	-	-	<i>"none" refers to subsistence-based arable farming</i>
SURPLUS-TAKEOFF	0-1	0.01	0.7	<i>Percentage of surplus grain removed from</i>

				<i>each settlement each year</i>
DAILY-PER-CAPITA-FUEL-USE	0-99	0.1	5	<i>Fuel consumption (kg) per inhabitant per day</i>
COPPICING?	"TRUE", "FALSE"	-	"TRUE"	<i>If "TRUE", settlements will manage areas of coppiced woodland within their catchment</i>
COLLECTION-FREQUENCY	1-365	1	1	<i>Frequency that inhabitants of each settlement must collect fuel. 1 = daily, 365 = once per year.</i>
RECONSTRUCTION-FREQUENCY	1-999	1	20	<i>Frequency that settlement buildings must be rebuilt. 1 = every year.</i>
CATTLE?	"TRUE", "FALSE"	-	"TRUE"	<i>If "TRUE", settlements manage a cattle herd</i>
SHEEP?	"TRUE", "FALSE"	-	"TRUE"	<i>If "TRUE", settlements manage a sheep herd</i>
HORSE?	"TRUE", "FALSE"	-	"FALSE"	<i>If "TRUE", settlements manage a horse herd</i>
SHEEP-STRATEGY	"meat", "milk", "wool"	-	-	<i>Animal husbandry strategy undertaken by settlements for sheep herds</i>
CATTLE-STRATEGY	"meat", "milk", "manure"	-	-	<i>Animal husbandry strategy undertaken by settlements for cattle herds</i>

Appendix 1. User-defined parameters in ROMFARMS

TYPE	VARIABLE	DESCRIPTION
PATCH	Raster-value	Value inherited from raster file
	Patch-owner	Settlement whose catchment patch is in
	Landscape-type	Landscape element type: "levee", "flood-basin", "other"
	Use	Identifies whether a patch contains coppiced woodland, unmanaged woodland, fen woodland or a settlement. Otherwise value is "none".
	Biomass	Quantity of wood (kg) in patch in current step
	Countdown-fallow	Number of years remaining before patch can be reused for arable land in current step
	Countdown-reforest	Number of years remaining before woodland regenerates in patch. in current step
SETTLEMENT	No-households	Maximum number of households
	Age	Age of settlement in steps in current step
	People	List of inhabitants in settlement in current step
	Livestock	List of animals owned by settlement in current step
	Catchment	List of patches in settlement's catchment area
	Calories-required	Total number of calories (kCal) required per year by settlement's inhabitants in current step
	Min-grain-store	Minimum quantity of grain (kg) required by settlement's inhabitants for consumption, sowing seed and buffer in current step
	Ploughing-labour-1	Average time (hrs) spent by one member of "strong" workforce in settlement on ploughing in current step
	Ploughing-labour-2	Total time (hrs) spent by whole "strong" workforce in settlement on ploughing in current step
	Sowing-labour-1	Average time (hrs) spent by one member of "strong" workforce in settlement on sowing in current step
	Sowing-labour-2	Total time (hrs) spent by whole "strong" workforce in settlement on sowing in current step
	Manuring-labour-1	Average time (hrs) spent by one member of "strong" workforce in settlement on applying manure to arable land in current step
	Manuring-labour-2	Total time (hrs) spent by whole "strong" workforce in settlement on applying manure to arable land in current step
	Harvesting-labour-1	Average time (hrs) spent by one member of "strong" workforce in settlement on harvesting in current step
	Harvesting-labour-2	Total time (hrs) spent by whole "strong" workforce in settlement on harvesting in current step
	Grain-store	Total quantity of grain (kg) settlement possesses in current step
	Max-arable-land-land	Total area of arable land (ha) available to settlement in current step
	Max-arable-land-grain	Maximum area of arable land (ha) settlement can sow with available grain in current step
	Max-arable-land-labour	Maximum area of arable land (ha) "strong" workforce in settlement can harvest in two weeks in current step
	Min-arable-land	Minimum area of arable land (ha) needed to produced minimum amount of grain required by settlement's inhabitants in current step
	Arable-land	Total area of arable land (ha) cultivated by settlement in current step
	Yield-grain	Total yield of grain (kg) produced by settlement in current step
	Surplus-grain	Total quantity of surplus grain (kg) produced by settlement in current step
	Grain-deficit	Total quantity of grain (kg) still required but not produced by settlement in current step
	SNM	Total number of own neonatal sheep slaughtered by settlement in current step
	CNM	Total number of own neonatal cattle slaughtered by settlement in current step
	SYM	Total number of own young sheep slaughtered by settlement in current step
	CYM	Total number of own young cattle slaughtered by settlement in current step
	SIM	Total number of own immature sheep slaughtered by settlement in current step

PERSON	CIM	Total number of own immature cattle slaughtered by settlement in current step
	SAM	Total number of own adult sheep slaughtered by settlement in current step
	CAM	Total number of own adult cattle slaughtered by settlement in current step
	Cattle-meat-yield	Total amount of meat from slaughtered cattle (kg) produced by settlement in current step
	Sheep-meat-yield	Total amount of meat from slaughtered sheep (kg) produced by settlement in current step
	Cattle-milk-yield	Total amount of milk from cattle (l) produced by settlement in current step
	Sheep-milk-yield	Total amount of milk from sheep (l) produced by settlement in current step
	Sheep-wool-yield	Total amount of wool from sheep (kg) produced by settlement in current step
	Cattle-manure-yield	Total amount of manure from cattle (kg) collected by settlement in current step
	Horse-surplus	Total number of surplus immature horses bred by settlement in current step
	Pasture-land	Total area of grazing land (ha) required by all livestock owned by settlement in current step
	Meadow-land	Total area of grassland (ha) needed to produce winter fodder for all livestock owned by settlement in current step
	Fodder-labour-1	Average time (hrs) spent by one member of “strong” workforce in settlement on harvesting in current step
	Fodder-labour-2	Total time (hrs) spent by whole “strong” workforce in settlement on harvesting in current step
	Fuel-workforce	List of settlement’s inhabitants in foraging group for fuel in current step
	Fuel-store	Total quantity of fuel (kg) settlement possesses in current step
	Fuel-target	Current patch foraging group of settlement is targeting for fuel collection
	Fuel-requirement	Total quantity of fuel (kg) that needs to be collected by foraging group in current trip
	Fuel-labour-1	Average time (hrs) spent by one member of fuel foraging group in settlement on fuel-collection in current step
	Fuel-labour-2	Total time (hrs) spent by whole “strong” workforce in settlement on fuel-collection in current step
	Construction-requirement	Total quantity of timber (kg) needed to rebuild buildings in settlement
	Construction-store	Total quantity of timber (kg) settlement possesses in current step
	Construction-target	Current patch foraging group is targeting for timber collection
	Construction-workforce	List of settlement’s inhabitants in foraging group for timber in current step
	Construction-labour	Total time (hrs) spent by whole timber foraging group in settlement on fuel-collection in current step
	Sex	-
	Age	Age of settlement in steps in current step
	My-spouse	Identifier of other person that is person’s spouse in current step
	My-house	Identifier of settlement that person resides in in current step
	Distance-travelled-fuel	Total distance travelled (km) whilst foraging for fuel in current step
	Distance-travelled-construction	Total distance travelled (km) whilst foraging for timber in current step
	Count-children	Total number of children borne to person up to current step
	Mortality	Probability that person will die in current step
	Fertility	Probability that person will produce one offspring in current step
	Load	Quantity of fuel or timber (kg) being carried by person in current step
	Max-load	Maximum load of fuel or timber (kg) that can be carried by person
	Processing-time-fuel	Total time (hrs) spent by person in a patch processing wood for use as fuel in current step
	Processing-time-timber	Total time (hrs) spent by person in a patch processing wood for use as timber in current step
ANIMAL	Age	Age of animal in steps in current step

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	Sex	-
	Species	Identifies whether animal is sheep, cattle or horse
	Fertility	Probability that animal will produce one offspring in current step
	Survivorship	Probability that animal will die of natural causes in current step
	My-owner	Identifier of settlement which owns animal
	Lactating	Identifies whether an animal is lactating in current step

Appendix 2. Mutable named variables in ROMFARMS

VARIABLE	VALUE	UNIT	SOURCE	NOTES
CALORIES-IN-CROPS	3100	kCal/kg	Kooistra, 1996, 67; van Dinter <i>et al.</i> 2014, 45, 49	
FALLOW-TIME	2	years	Van Dinterf <i>et al.</i> 2014, 45	
BASIC-YIELD	1000	Kg/ha	Kooistra, 1996, 67; van Dinter <i>et al.</i> 2014, 45, 49	
SOWING-RATE	200	Kg/ha	Kooistra, 1996, 67; van Dinter 2014, 45,49	
YIELD-INCREASE-MANURE	15	Kg per kg of N	Shiel 2012, 20	
N-CONTENT-MANURE	6	Kg/t	Chamber <i>et al.</i> 2001, 6, table 1	
SOWING-TIME	3	Hrs/ha	Sigaut 1992	
PLOUGHING-TIME	30	Hrs/ha	Steensberg 1986; Reynolds 1987	
HARVESTING-TIME	48	Hrs/ha	Dinter <i>et al.</i> 2014, 49; see also Gregg 1988, 161-162	
MANURING-TIME	30	Hrs/ha	Best guess	
ADULT-WEIGHT-CATTLE	200	Kg/animal	van Dinter <i>et al.</i> 2014, 46; see also IJzereef 1981; Reichstein 1984; Brinkkemper 1991; Prummel 1992	
IMMATURE-WEIGHT-CATTLE	150	Kg/animal	van Dinter <i>et al.</i> 2014, 46	
YOUNG-WEIGHT-CATTLE	35	Kg/animal	van Dinter <i>et al.</i> 2014, 45; see also IJzereef 1981	
ADULT-WEIGHT-SHEEP	25	Kg/animal	IJzereef 1981; see also Gregg 1988, 116	
IMMATURE-WEIGHT-SHEEP	18.75	Kg/animal	van Dinter <i>et al.</i> 2014, 46	
YOUNG-WEIGHT-SHEEP	10	Kg/animal	Gregg 1988, 116	
%-EDIBLE-CARCASS-CATTLE	60	% live weight	van Dinter <i>et al.</i> 2014, 46	
%-EDIBLE-CARCASS-SHEEP	30	% live weight	IJzereef, 1981	
MILK-YIELD-CATTLE	1.2	L/day/animal	Bekure <i>et al.</i> 1991, section 7.17	
LACTATION-LENGTH-CATTLE	200	Days	Gregg 1988, 106	
MILK-YIELD-SHEEP	0.2	L/day/animal	After Redding 1981	
LACTATION-LENGTH-SHEEP	135	Days	Gregg 1988, 116; see also Redding 1981	
WOOL-YIELD-SHEEP	2	Kg/immature or adult animal	Wild 1970; WildFibres 2008- 2016	
MANURE-DAILY-YIELD	6	% body weight/day	Fokkens 1991; IJzereef 1981	
TWINNING-RATE-SHEEP	0.2	-	Best guess	<i>Probability of adult sheep producing two offspring</i>
ALPHAS	7.5	Yrs	Best guess	<i>Age of senescence (sheep)</i>
ALPHAC	17.5	Yrs	Best guess	<i>Age of senescence (sheep)</i>
ALPHAH	27.5	Yrs	Best guess	<i>Age of senescence (sheep)</i>

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ALPHA	2.5	Yrs	Best guess	<i>Std. dev. age of senescence</i>
NEONATAL-MORTALITY-SHEEP	0.32	-	Gregg 1988, 104,113; see also Perry 1984	<i>Probability of death</i>
NEONATAL-MORTALITY-CATTLE	0.2	-	Gregg 1988, 104,113; see also Perry 1984	<i>Probability of death</i>
NEONATAL-MORTALITY-HORSE	0.2	-	Gregg 1988, 104,113; see also Perry 1984	<i>Probability of death</i>
ANNUAL-MORTALITY-RATE	0.014	-	Galic 2014	<i>Background annual mortality rate of animals</i>
FODDER-SHEEP	252kg	Kg/adult animal/4 months	-	<i>1/3 requirement adult cattle (see pasture land requirements)</i>
FODDER-CATTLE	756	Kg/adult animal/4 months	van Dinter <i>et al.</i> 2014, 47; see also Groenman-van Waateringe & van Wijngaarden-Bakker 1987	
FODDER-HORSE	756	Kg/adult animal/ 4 months	van Dinter <i>et al.</i> 2014, 47; see also Groenman-van Waateringe & van Wijngaarden-Bakker 1987	
PASTURE-LAND-SHEEP	0.111	Ha/adult animal/8 months	Fokkens 1991, 131	
PASTURE-LAND-CATTLE	0.33	Ha/adult animal/8 months	van Dinter <i>et al.</i> 2014, 46-47	
PASTURE-LAND-HORSE	0.33	Ha/adult animal/8 months	Kooistra 1996, 72; Woltering 2000	
YIELD-GRASSLAND	3000	Kg/ha	Kreuz 1995, 81	
WALKING-SPEED	5	Km/hr	Pandolf <i>et al.</i> 1977	
MAX-LOAD-ADULT-MALE	30	Kg/person	Gregg 1988, 162	
MAX-LOAD-ADULT-FEMALE	20	Kg/person	Gregg 1988, 162	
MAX-LOAD-OTHER	15kg	Kg/person	Best guess	
FUEL-COLLECTION-TIME	3	Hrs/person/patch	Brouwer <i>et al.</i> 1997, 260, table 2	
TIMBER-COLLECTION-TIME	6	Hrs/person/patch	Best guess	

Appendix 3. Immutable named variables in ROMFARMS.